The Taphonomy of Historic Shipwreck Sites

by

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An understanding of the extent to which materials and energy are free to exchange across boundaries at shipwreck sites is fundamental to the archaeological interpretation of these unique resources. The limited previous work on the dynamics of shipwreck sites suggest that they can act as either near-closed systems (e.g. Mary Rose), or open systems at some state of dynamic/quasi-equilibrium with respect to their surroundings’ (e.g. Stirling Castle). Nonetheless, our understanding of the temporal evolution of shipwreck sites and thus, whether they are open or closed systems, is extremely limited.

This thesis presents repeat (intra-annual; annual; and decadal) Multibeam Echosounder (MBES) surveys for five shipwreck sites (the largest published collection of shipwreck site MBES time-series to date) from a range of environments: the Richard Montgomery, tidally dominated (weakly asymmetrical); the Scylla, storm dominated; the Burgzand Noord site, tidally dominated (strongly asymmetrical); the Stirling Castle, dominated by large-scale geomorphological processes; and the Algerian, sheltered. By quantifying the temporal variability (through bed-level change plots) and the Metocean, geological and geomorphological conditions of these wreck sites, the impact of the differing marine environments on the wreck site’s taphonomic pathway was constrained.

Through the collation of these MBES time-series the importance of being able to account for the uncertainty of the data when comparing two time steps was realised. To this end, a robust methodology for assessing the uncertainty of the MBES data was developed for the use with marine MBES data.

The spatial patterns of scouring and deposition were accounted for through the application of the simple principles of scouring around bluff obstacles (cylinders, cuboids and piers etc.). Those sites which experienced a disturbance during the observation period (e.g. a storm event at the Scylla, sandbank migration at the Stirling Castle and the implementation of physical protection at the Burgzand Noord site) underwent a larger range of bed-level change and altered dramatically in their scour/deposition arrangement. Those sites at quasi-equilibrium (SS Richard Montgomery, Algerian and Scylla for the final time-step) underwent no perceivable net bed-level change over the observation period and had stable scour and deposition features.

The comprehension of shipwreck site taphonomy gained through this thesis is fundamental to the efficacy of heritage management, allowing protective measures to be site-tailored and fills a large data- and knowledge-gap in the long term (multi-annual) evolution of scour around marine anthropogenic structures.
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Declaration of Authorship

I, Amelia J. Astley, declare that the thesis entitled The Taphonomy of Historic Shipwreck Sites and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published as: Astley et al. (2014), Astley et al. (2015), Astley (in review, b) and Astley et al. (in review, a)

Signed:...............................................................................................................................

Date:...............................................................................................................................

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Throughout my PhD I have made use of a range of freely available data, including: archaeological reports from the National Archives, British Library, Southampton City Library, and www.kenthistoryforum.co.uk; Meteorological and oceanographic (Metocean) data from the BODC, CCO, Canterbury City Council and CEFAS; bathymetry from UKHO Inspire; and geological data from the BGS.

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# Nomenclature

\[ \begin{align*}
A & \quad \text{orbital amplitude of wave motion at the bed} \\
C_D & \quad \text{dimensionless drag coefficient} \\
D_* & \quad \text{dimensionless grain size} \\
d_{50} & \quad \text{median grain size} \\
f_{wr} & \quad \text{rough-bed wave friction factor} \\
f_{ws} & \quad \text{smooth-bed wave friction factor} \\
g & \quad \text{acceleration due to gravity} = 9.81 \text{ms}^{-2} \\
h & \quad \text{water depth} \\
H_s & \quad \text{significant waveheight} \\
k_s & \quad \text{Nikuradse equivalent sand grain roughness} \\
R_W & \quad \text{wave Reynolds number} \\
s & \quad \text{ratio of densities of grain and water} \\
T_n & \quad \text{scaling period for waves} = \frac{h^{1/2}}{g} \\
T_Z & \quad \text{zero crossing period of waves} \\
U(0) & \quad \text{surface current velocity} \\
\bar{U} & \quad \text{depth-averaged current speed} \\
U_{rms} & \quad \text{root-mean square wave orbital velocity at seabed} \\
U_w & \quad \text{bottom orbital velocity amplitude} \\
v & \quad \text{kinematic viscosity of the fluid} \\
z & \quad \text{height above seabed} \\
z_0 & \quad \text{hydraulic roughness length} \\
\theta_{2.5,cr} & \quad \text{Shields threshold for motion} \\
\theta_{2.5} & \quad \text{Shields parameter calculated with } K_s = 2.5d_{50} \\
\phi & \quad \text{angle between the wave and current shear} \\
\rho & \quad \text{fluid density} \\
\rho_s & \quad \text{density of of the grain mineral} \\
\tau_c & \quad \text{current related bed shear stress} \\
\tau_{cr} & \quad \text{critical shear stress} \\
\tau_m & \quad \text{combined wave-current motion} \\
\tau_{max} & \quad \text{maximum shear stress} \\
\tau_w & \quad \text{wave related bed shear stress}
\end{align*} \]
Glossary

ADU  Archaeological Diving Unit.
AUV  Autonomous Underwater Vehicle.
AWAC Acoustic Wave and Current.
BODC British Oceanographic Data Centre.
CCO Channel Coastal Observatory.
CD  Chart Datum.
CFD Computational Fluid Dynamics.
CUBE Combined Uncertainty Bathymetric Estimator.
DEFRA Department for Environment, Food & Rural Affairs.
DEM Digital Elevation Model.
DERA Defence Evaluation and Research Agency.
DGPS Differential GPS.
DoD DEM of Difference.
FIS Fuzzy Inference System.
GCD Geomorphic Change Detection.
GNSS Global Navigation Satellite System.
GPS Global Positioning System.
HVF HIPS Vessel File.
IARTK Inertially-Aided Real Time Kinematic.
IDW Inverse Distance Weighting.
IHO International Hydrographic Organisation.
IMU Inertial Measurement Unit.
KC Keulegan-Carpenter.
LiDAR Light Detection And Ranging.
LoD_{min}  minimum level of detection threshold.
MACHU  Managing Cultural Heritage Underwater.
MAS  Marine Archaeological Surveys.
MBES  Multibeam Echo-Sounder.
MCA  Maritime and Coastguard Agency.
Metocean  Meteorological and oceanographic.
MoD  Ministry of Defence.
MoSS  Monitoring of Shipwreck Sites.
NAP  Normal Amsterdam Level.
NEQ  Net Explosive Quantity.
NMA  National Marine Aquarium.
OD  Ordnance Datum.
PLA  Port of London Authority.
QF  Quality Factor.
RASSE  Rapid Archaeological Site Surveying and Evaluation.
RMS  Root Mean Squared.
ROV  Remotely Operated Vehicle.
RSS  Root Sum Squared.
RTK  Real Time Kinematic.
SOG  Speed Over Ground.
SSV  Surface Sound Velocity.
SVP  Sound Velocity Profile.
THU  Total Horizontal Uncertainty.
TIN  Triangulated Irregular Network.
ToPCAT  Topographic Point Cloud Analysis Toolkit.
TPU  Total Propagated Uncertainty.
TVU  Total Vertical Uncertainty.
TWT  Two-Way Time.
UKHO  United Kingdom Hydrographic Office.
VORF  Vertical Offshore Reference Frame.
WA  Wessex Archaeology.
WWII  World War II.
Chapter 1

Introduction

1.1 Introduction to the problem

The understanding of the preservation potential of shipwreck sites has grown beyond the initial concept that the marine environment was destructive and only capable of preservation in extreme circumstances (Throckmorton, 1977, p.47). Now site-formation (taphonomic) processes are considered as a mechanism which can be identified, understood and potentially reverse-engineered to an extent at almost all wreck sites (Church, 2014; Muckelroy, 1976; O’Shea, 2004; Tomalin et al., 2000). In this thesis time-series of multi-beam bathymetry surveys are employed to quantify the temporal change in the seabed surrounding historic shipwreck sites. Through an assessment of the hydrodynamic and geological conditions of the site the role of environmental conditions on shipwreck site taphonomy can be better understood. This study impacts significantly on two areas of research: heritage management and long term (multi-annual) evolution of scour around marine anthropogenic structures (e.g. windfarm turbines, pipelines and breakwaters).

1.2 Motivation

1.2.1 The value of historic shipwreck sites

There are over 3 million shipwrecks worldwide (UNESCO, 2014); of these more than 60,000 are recorded to have sunk within UK territorial waters, of which approximately 20,000 are named vessels (Figure 1.1; Cant, 2013). Archaeologists have long recognised the value of shipwrecks which arises from three key elements:

i. The abrupt formation of shipwreck sites allows archaeologists to infer relationships between artefacts as they all share a common source: the vessel. By comparison the
Chapter 1 Introduction

Figure 1.1: Distribution of wreck sites across northwestern Europe. The bathymetric metadata and Digital Terrain Model data products have been derived from the EMODnet Bathymetry portal - http://www.emodnet-bathymetry.eu. Wreck locations are sourced from the United Kingdom Hydrographic Office (UKHO) Wrecks database.

time-scales over which items are discarded on land may differ considerably, often resulting in the loss of these relationships (Schiffer, 1987).

ii. The self-regulating nature of ships creates an archaeological deposit which incorporates a wide range of materials, some of which reflect land-based items and others of which have been adapted for use at sea or are unique to maritime activities (Adams, 2001). As a result of this, marine sites can not only be used to supplement the historical and terrestrial records, but also are used as a crucial counterpoint to the terrestrial record.

iii. The immense potential for preservation on wreck sites presents a more complete range of artefacts. For example, exquisitely preserved wood, leather and rope items have been recovered from wreck sites such as the Kennemerland (Price and Muckelroy, 1977), La Trinidad Valencera (Martin, 1975) and Mary Rose (Marsden, 2003). When used alongside terrestrial archaeological artefacts this creates a full picture of the period of time in question.

Therefore, it is paramount that these invaluable archaeological resources receive treatment which allows for the greatest volume and detail of archaeological information to be extracted; whether this is through present-day site investigation and/or excavation, or through the preservation and management of the site in situ for some future investigation (presently the UNESCO recommended strategy; UNESCO, 2002). For the former
we must have an understanding of how the site formed and for the latter we must have an understanding of the future trajectory of the site to confirm whether or not in situ preservation is a viable option. Both of these require knowledge of the wreck site taphonomy. The current state of knowledge of these processes is explored in the following three sections.

1.2.2 The taphonomy of historic shipwreck sites

The processes which govern the trajectory of a wreck site from its initial wrecking to present day (e.g. burial, erosion, salvage, redistribution of material, and anthropogenic impacts such as looting and dredging) are defined here as the taphonomy of the shipwreck site. Originally a palaeontological term used to describe the relationships between post-mortem organic remains and their external environment (Efremov, 1940), taphonomy first entered the archaeological language in the mid 1970’s (Boaz and Behrensmeyer, 1976). The word is an amalgamation of two Greek words taphos, for burial and nomos, for laws (Martin, 1999). It has been argued that the adoption of this term by archaeologists is a misinterpretation and dilution of its original meaning since archaeological artefacts and sites include items which were at no point living (Lyman, 2010). However, whilst no other succinct terminology exists to describe the processes that take place between artefact deposition and the present time and as in many other branches of science, terminology is allowed to evolve with time to become inclusive of a larger body of work (Slisko and Dykstra, 1997). For the purpose of this thesis the term taphonomy shall be used. Just as many archaeologists have used it over the past half century, it is used here to describe the relationships between archaeological deposits (in this circumstance shipwrecks) and their external environment.

The false assumption is often made that spatial relationships between artefacts at shipwreck sites are lost through taphonomic processes (Dumas, 1972). However, whilst at shipwreck sites taphonomic processes can lead to the weakening of patterns and associations, and the creation of new and potentially spurious patterning (O’Shea, 2002), so long as their effects can be well constrained then distortions can be corrected for by using analytical and inferential tools (Schiffer, 1987). Therefore, even disaggregated wreck sites can still have determinable relationships and thus enhanced archaeological value.

1.2.3 Approaches for constraining the taphonomy of shipwreck sites

In this section, past approaches for constraining taphonomic processes introduced in the previous section are described and their merits and weaknesses discussed.
1.2.3.1 Single survey

The latter half of the 20thC was a time of great change in the field of maritime archaeology. This period of time heralded the migration from a treasure-hunter’s pursuit to a discipline with protocols and a growing understanding of the importance of the seafloor environment on the preservation of shipwreck sites. Crucially, an appreciation for the significance of the spatial relationships between artefacts and the wreck superstructure was realised. With whole site surveys still being conducted primarily by diver teams, repeat surveys of sites were seldom carried-out and when available, were often lacking in the detail necessary to capture fine-scale (sub-metres) change. Instead archaeologists based much of their assessments of the taphonomy of wreck sites upon singular surveys.

In his pioneering work, Muckelroy (1975) used the wreck of the Kennemerland, located off the Shetland Isles, to illustrate the methods for interpreting internal processes (scrambling devices). The Kennemerland wreck exists in an environment destructive enough to remove the hull, yet artefacts remain in distribution which reflects position on-board the ship. Muckelroy (1975) noted that the cargo, provisions and possessions of occupants were in distinct patches on the seafloor. These “microdistributions” (Muckelroy, 1976, p.287) were found to be statistically correlated to shipboard associations. Strong clustering was identified as a sign that there has been little resorting on the Kennemerland site. However, transportation of artefacts had occurred in the direction of the dominant wind forcing. The different locations of parts of clay pipes were taken to indicate that some parts of the site were more prone to destruction (Muckelroy, 1975).

Quinn et al. (1998) took a more oceanographic approach to resolving the transport of artefacts on wreck sites. However, with only a site plan from present day they could only observe the net transport of artefacts which had accrued over the 240 years they had spent on the seafloor. By studying the tidal regime, dominant storm forcing and the bedforms of the area surrounding the wreck of the Invincible in the east Solent, Quinn et al. (1998) were able to decipher the forces responsible in shaping the distribution of the wreck, which was inspected using Chirp and side-scan profiling. The predominant tidal flow over the site is to the north-northwest, this could not explain the spread of artefacts to the north and north-east of the coherent wreckage. Storm data on the other hand revealed that 90% of storm events of Force 8 or higher were south or south-westerlies, this could, therefore, be used to explain the distribution of artefacts at this site.

These two examples clearly demonstrate how with a single site plan and a basic understanding of the prevailing forces the net trajectory of the site can be accounted for. However, because of the dynamic or steady state nature of shipwreck sites it is important to recognise that a single time-step survey can only ever describe the site at one point in time. This snapshot of the site may, or may not, be representative of the prevailing conditions and equally, sheds little light on the temporal variability of these sites.
1.2.3.2 Transportation trials

The second approach discussed in this section, transportation trials, is arguably the most simplistic of the techniques covered. In brief, the main technique used in transportation trials is to place some objects (bricks, golf balls, ceramics etc.) on the seafloor and record their position. After a period of time the locations of the objects are then re-recorded. This provides a quantitative description of the net transport of the chosen items. From this the prevailing transport direction at the site can be inferred. Such trials were first used to trace the transport of sediment in riverine and marine settings (White, 1998) and were later adapted for use at archaeological sites. Their reliable and empirical nature have meant that transportation trials have generated good results in the past.

A number of transportation trails have been carried out on wreck sites around the British Isles. The first of which was conducted on the same site as many of the studies of Muckelroy (1976) focused on, the Kennemerland. This study was carried out by Dobbs and Price (1991), who, in 1976, placed a number of broken and complete flowerpots on the wreck site. Their positions were then recorded again in 1978. Unfortunately no comment was made on their movement, so nothing can be said of the environmental conditions of the site; however, this experiment was the first step towards gaining an understanding of the dynamics and the temporal scales of shipwreck sites.

In another transportation trial, at the site of the Kinlochbervie wreck, weighted golf balls and tennis balls were placed at differing water depths (Robertson et al., 2004). At the deep end of the Kinlochbervie site the golf balls were found relatively close to their initial positions, indicating a fairly low net annual transportation. Those placed in the shallows were not retrieved and were thought to have been carried away from the site. Robertson et al. (2004) found that under the Muckelroy (1977) classification system the Kinlochbervie site straddled two classes. In the shallow water, where the site was highly dispersed, the site fitted into the class 5 category. However, in the deep water, where storm surges had little influence, the site fitted into the class 4 category (Robertson et al., 2004). This understanding of the site has allowed archaeologists to prioritise their efforts to the deep water end of the site, as this part of the site is more likely to have preserved artefacts and maintained spatial relationships.

Previous dispersal trials on the Kennemerland (Dobbs and Price, 1991), Royal Anne Galley (English Heritage, 2011), Kinlochbervie (Robertson et al., 2004), Hazardous Prize and St Peter port harbour wrecks (Holland, 2005) have made limited attempts to use hydrological data to interpret transport. Furthermore, different tracers were used at each site and the transport properties of each tracer were not confined in any of the studies; this limits the comparability of these different trials. Whilst these studies have illuminated

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1The Muckelroy (1977) classification system sought to group together wreck sites according to their environmental conditions using the following five variables: topography, deposit, slope, sea horizon and fetch. At one end of the spectrum class 1 site was a sheltered, flat and sandy site and at the other a class 5 site was an exposed, steep and rocky site.
the transport pathways of objects at these sites, limited conclusions can be ascertained as to the broader transport patterns of both artefacts as well as sediment which ultimately impacts upon the overall preservation of the site (Ward et al., 1999).

1.2.3.3 Multibeam bathymetry time-series

Geophysical tools have been employed by underwater archaeologists since the 1960’s (Rosencrantz et al., 1972). For several decades sidescan sonar remained the workhorse of marine geoarchaeologists and was utilised in searching for wrecks of unknown location and to provide primarily qualitative information about the wreck structure and site layout. It wasn’t until the late 1980’s that Multibeam Echo-Sounder (MBES) systems capable of achieving high-resolution (<1m point spacing) bathymetry surfaces in shallower water became available. Their uptake in marine archaeology was not instant; other hurdles had to be overcome including the requirement for data storage (a single day of surveying could generate a data file of over 10 GB in size (Bowens, 2009). Furthermore, the cost of each system initially prevented non-commercial enterprises from using the devices. Once these obstacles were surpassed the full potential of MBES was realised; surveys could now be conducted at rates more than 100,000 times faster than diving teams (Bowens, 2009). Finally archaeologists had a tool they could use to rapidly carry out high resolution bathymetric surveys of wreck sites.

Before MBES could be used to quantify temporal change at a wreck site an increase in the accuracy of the positioning was required, so that when sites were resurveyed the surfaces could be matched up and subtracted from one-another, generating bed-level change plots. With the completion of the first Global Navigation Satellite System (GNSS) in 1995, Global Positioning System (GPS), horizontal positional accuracy at sea was in the region of ±10m. By incorporating high-precision land-based reference stations, Differential GPS (DGPS), horizontal accuracy was improved to approximately 1-5m. This accuracy can be enhanced further, to within just a few centimetres, through signal phase analysis as in the case of Real Time Kinematic (RTK) GPS and Inertially-Aided Real Time Kinematic (IARTK) (the latter utilizes the inertial data from the vessel to provide robust positioning even when there is GPS signal outage). Through these techniques it is ensured that seabed features, e.g. shipwrecks and their associated scour pits’, are accurately matched (in x, y, z space) and compared between MBES surveys.

Despite high resolution MBES systems now being relatively affordable and accessible to maritime archaeologists, just seven projects have employed time-series of MBES to quantify historical shipwreck site variability and reported their findings (Table 1.1, Figure 1.2). Of these, just four peer-reviewed journal papers incorporating time-series of bathymetry surveys of archaeological wreck sites have been published (Bates et al., 2007; Brennan et al., 2016; Quinn and Boland, 2010; Stieglitz and Waterson, 2013). Perhaps one of the longest and most extensive MBES time-series project, the Burgzand Noord site project,
Table 1.1: MBES time-series where the target was a wreck site. Surveys included within publication and Unpublished existing surveys.

<table>
<thead>
<tr>
<th>Wreck</th>
<th>Reference</th>
<th>No. of surveys</th>
<th>Minimum survey spacing</th>
<th>Total length of time-series</th>
<th>Depth of site</th>
<th>Date of wrecking</th>
<th>Environmental conditions</th>
<th>Scouring Observed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stirling Castle</td>
<td>Bates et al. (2007) 51, 62</td>
<td>5</td>
<td>5 months</td>
<td>4 years1, 7 year2</td>
<td>15m</td>
<td>1703</td>
<td>Dominated by bank scale (km) migration</td>
<td>Yes</td>
</tr>
<tr>
<td>Bow sprit wreck</td>
<td>Bates et al. (2007)</td>
<td>4</td>
<td>5 months</td>
<td>1.5 years</td>
<td>15m</td>
<td>Unknown</td>
<td>Same as above</td>
<td>Yes</td>
</tr>
<tr>
<td>Burgzand Noord wrecks</td>
<td>Manders (2009); van den Brenk et al. (2014)</td>
<td>13</td>
<td>1 year (4 days over small area)</td>
<td>11 years</td>
<td>7-10m</td>
<td>16-19thC</td>
<td>Deepening of seafloor in response dyke construction</td>
<td>Yes</td>
</tr>
<tr>
<td>Hoornsche Hop 2</td>
<td>Manders (2009)</td>
<td>2</td>
<td>5 months</td>
<td>5 months</td>
<td>14m</td>
<td>18thC</td>
<td>Not stated</td>
<td>Yes</td>
</tr>
<tr>
<td>SS Yongala</td>
<td>Stieglitz and Waterson (2013)</td>
<td>3</td>
<td>3 years</td>
<td>7 years</td>
<td>28m</td>
<td>1911</td>
<td>Cyclone events</td>
<td>Yes</td>
</tr>
<tr>
<td>Arklow bank wreck</td>
<td>Quinn and Boland (2010)</td>
<td>2</td>
<td>11 days</td>
<td>11 days</td>
<td>15m</td>
<td>19thC</td>
<td>Live-bed, tidally dominated</td>
<td>Yes</td>
</tr>
<tr>
<td>Ereğli E.</td>
<td>Brennan et al. (2016)</td>
<td>2</td>
<td>11 months</td>
<td>11 months</td>
<td>100m</td>
<td>4th C BC</td>
<td>Featureless, sandy</td>
<td>No</td>
</tr>
<tr>
<td>SS Virginia</td>
<td>Orange and García-garcía (2009)</td>
<td>2</td>
<td>2 years</td>
<td>2 years</td>
<td>-</td>
<td>1942</td>
<td>Mud flows initiated by hurricane events</td>
<td>No</td>
</tr>
<tr>
<td>Redbird artificial reef</td>
<td>Trembanis et al. (2013)</td>
<td>3</td>
<td>15 days</td>
<td>&lt;2months</td>
<td>28m</td>
<td>Modern</td>
<td>Impact of a single hurricane</td>
<td>Yes</td>
</tr>
<tr>
<td>Wadden sea dingy</td>
<td>Ernstsen et al. (2006a)</td>
<td>11</td>
<td>&lt;1 day</td>
<td>4 years</td>
<td>28m</td>
<td>Modern</td>
<td>Asymmetrical tides</td>
<td>Yes</td>
</tr>
</tbody>
</table>
has not been published within any journal papers, but has been published within the final Managing Cultural Heritage Underwater (MACHU) report (Manders, 2009) and in a Dutch language report (van den Brenk et al., 2014). Within the Manders (2009) report two distinct wreck sites are examined with MBES time-series (the Burgzand Noord wreck site is counted just once since all 14 wrecks are within a 0.73km$^2$ area, and therefore, are subject to very similar prevailing environmental conditions).

Three further shipwrecks have associated MBES time-series (the last three entries in Table 1.1). However, all three of these projects had non-archaeological objectives, i.e. the wrecks were either part of an artificial reef (Trembanis et al., 2013), used for determining the uncertainties of MBES surveys (Ernstsen et al., 2006a) or used to track the seasonal variability in seafloor acoustic properties (Orange and García-garcía, 2009). These time-series still feature within this review since the only differences between these projects and the aforementioned archaeological projects is the length of time for which the vessel has been on the seafloor and the nature of the analysis performed on the MBES time-series.

From this appraisal of the present state of the use of MBES time-series at wreck sites it is clear that datasets are few and far between. Often these datasets are not collected for quantification of the taphonomic processes at wreck sites and so are lacking in certain aspects. These caveats are now discussed alongside the merits of MBES time-series.

One of the first projects solely dedicated to quantifying the bathymetric change at a wreck site using MBES time-series was the Rapid Archaeological Site Surveying and Evaluation (RASSE) program (Bates et al., 2011). The aim of the RASSE research project
was to address the geophysical potential of sonar systems and their use in maritime ar-
chaeology. In the second phase of the project the *Stirling Castle* wreck, located in a gully in the Goodwin Sands bank system, was used as the working example site. As part of this project five MBES surveys were conducted at the site over a period of four years, alongside a whole suite of other geophysical surveys.

A major caveat of the MBES time-series was the absolute vertical accuracy of the surfaces; a uniform offset in the wreck position was observed between the surveys, which was at times in excess of 2 metres. To correct for this all surveys were vertically shifted to match the final, August 2006, survey. This relied on the assumption that the wreck super-
structure had not moved between surveys, the validity of which is brought into question later in this section.

The *Stirling Castle* study did however illustrate the usefulness of MBES time-series in quantifying the elevation change over a wide area surrounding the wreck site. Down-
stream of the wreck sediment has been scoured\(^2\), deepening the seafloor relative to the channel. The maximum level of elevation change within this scour pit from 2002 to 2006 was larger (≈-2.8m) than for the rest of the channel (≈-1m). From analysing the bed-
forms traversing the MBES surfaces the prevailing transport direction was determined. The directionality correlated well with the observed scouring downstream of the wreck.

Due to the long-scale temporal processes occurring at the *Stirling Castle* site (the migra-
tion of sandbank and sand-dunes) Bates *et al.* (2011) did not feel they could draw any solid conclusions with regards to the patterns of changes; suggesting that a total survey-
ing period of four years was insufficient to allow for future prediction of accretion-erosion at the site in such a dynamic setting.

Around the same time as the RASSE project two programmes were initiated as part of the Culture 2000 scheme: i) the Monitoring of Shipwreck Sites (MoSS) project, which ran from 2002 to 2004 and was based on four shipwrecks of great significance from a Eu-
ropean point of view and ii) MACHU, a three year long program (2006 to 2009) which set out to support new and better ways for effective management of underwater cultural heritage sites. Both projects shared a common case study, the Burgzand Noord wreck number 10, located in the Wadden Sea, Netherlands. Similarly to the RASSE project, time-series of MBES bathymetry surveys were used to generate bed-level change plots. Whilst the MoSS program only focused on BZN 10, the MBES surveys in fact extended

\(^2\)Scouring is the process by which flow past an obstacle is altered initiating flow acceleration and an increase in turbulent intensity, this in turn leads to the suspension and removal of sediment (Whitehouse, 1998). Scour is prevalent at almost all submerged bluff structures situated on an unconsolidated sediment bed and exposed to a current. Broadly, in terms of anthropogenic structures, this includes bridges, pier foundations, breakwaters, wind turbine foundations (monopiles, gravity based structures etc.), drilling rig risers and pipelines. It is of concern to marine engineers since the removal of sediment can lead to structural instability, damage to the structure and even structural collapse (Whitehouse, 1998). Therefore, an understanding of scour processes is key to the effective design and maintenance of these constructions.
over 14 wrecks. During the MoSS and MACHU phases of the program seven annual surveys were performed from 2002 to 2009 (Manders, 2009). However, this program continued past these two phases and has extended the yearly repeat surveys through to 2013, though these are presently only published within a Dutch technical report which is only accessible on request (van den Brenk et al., 2014).

Within the semi-enclosed sea in which the Burgzand Noord wrecks are located bed-level has been dramatically decreasing (at a rate of 0.05m a year) due in part to subsidence (0.006m a year), but largely due to the effects of the completion of two dykes: the Balgzand in 1924 and the Afsluitdijk in 1932. The construction of these dykes has radically reshaped the tidal prism of the region (van den Brenk et al., 2014). This has led to the exposure of over 14 wrecks in the Burgzand Noord area, many of which are now protected using sandbags and polypropylene nets. In the immediate area surrounding wreck number 10 bed-level deepened on average by 0.77m from 2002 to 2013, by comparison to the whole survey area which deepened by 0.49m over the same period of time. Despite this deepening in the area surrounding the wreck, the wreck structure remained largely intact. By contrast, wreck 11, left unprotected as a baseline, virtually disappeared through break-up and dispersal, during this period.

Through the comprehensive understanding of the sediment dynamics of the Burgzand Noord wreck site and the impact of differing heritage management strategies upon preservation more effective protection methods were developed through this project (Netherlands Institute for Ship and Underwater Archaeology (NISA), 2004). The Burgzand Noord project demonstrated the importance of temporal spacing of surveys in capturing different sedimentary processes; annual surveys showed the progressive bed-level loss of the basin and region of the wreck site, whereas, a survey spacing of just four days was effective at quantifying bed-load transport through migration of bedforms.

Whilst repeat surveys of the Burgzand Noord wrecks were conducted on an annual basis, at the Hoornse Hop 2 site (Manders, 2009) and both of the non-archaeological wreck sites (Ernstsen et al., 2006a; Trembanis et al., 2013) surveys were repeated within 5 months, 15 days and over just a single flood-ebb tidal cycle, respectively. The frequency of repeat surveys reflects the users’ objectives; at the Hoornse Hop 2 site the contractors of the MBES surveys were investigating illegal digging activity at the site and so were less-interested with long-term site change.

From two surveys performed at the Hoornse Hop 2 site a bed-level difference map was produced which highlighted the change between the August 2003 and the January 2004 survey (Manders, 2009). In this plot statistically insignificant change was designated as any values between ±0.1m, i.e. all values greater than this represented real change. Manders (2009) gave no mention of how the ±0.1m vertical uncertainty value was derived. However, it is likely that this was a estimation taken from software developers and instrument manufacturers which many MBES users rely on to gauge the vertical accuracy.
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of their surveys (Ernstsen et al., 2006a). Assessing and minimising the uncertainty of each MBES survey is critical to the analysis of bed-level change since if the uncertainty is greater than the real change then this change cannot be resolved using this methodology.

Ernstsen et al. (2006a) highlights that the achievable survey precision in the field may differ from the estimates used by Manders (2009) and others. Using four annual surveys on a sunken dinghy (assumed to be at a fixed location) they found that horizontal and vertical precision of their RTK MBES system in the field were ±0.30m and ±0.08m, respectively. As with the Stirling Castle project and many others it was assumed that the wreck’s location was static throughout the surveying period, and as it measured only 6.5m × 3.0m × 1.0m and was located in an area with mobile bedforms (Ernstsen et al., 2006b) this may have been a potentially negligent assumption. In extreme examples, such as the case of the wreck of the SS Virginia, in the Gulf of Mexico, which was transported 54m over two years by mud flows (Orange and García-garcía, 2009). Although an extreme case this highlights the potential positional instability of wreck structures and the importance in gathering data with regards to the hydrodynamic and geological conditions of the site.

Since the Ernstsen et al. (2006a) study was purely to assess the precision of MBES systems no comments were made on the development of the taphonomic processes occurring around the dinghy, unlike the Stieglitz and Waterson (2013) paper which, by contrast, aimed to quantify the effects of the Cyclone Yasi (2011) on the wreck and surrounding seafloor of the SS Yongala through a comparison of a 2004 and 2011 MBES surfaces. A systematic horizontal offset of 2m was observed between the 2004 and 2011 surveys. The authors do not state how this was determined, but they did correct for it before creating bed-level change maps. Somewhat surprisingly despite the rotation and movement of the bow of the wreck no significant change was observed in the bathymetry of the surrounding seabed.

Similarly to Stieglitz and Waterson (2013), Trembanis et al. (2013) aimed to use repeat MBES surveys to study the effects of a single storm event on the morphology of the seabed surrounding a man-made object (in the case of Trembanis et al. (2013) a Navy barge, a tugboat and a number of subway cars). Complementing the ship-based and Autonomous Underwater Vehicle (AUV) collected MBES time-series Trembanis et al. (2013) were also able to collate a time-series of in situ hydrodynamic conditions. Whilst a qualitative comparison is made between the bathymetry surfaces pre- and post-hurricane it is unfortunate that Trembanis et al. (2013) did not fully utilise the quantitative value of the MBES surfaces; even though they ensured the survey design and gridding parameters remained the same between surveys they did not produce any bed-level change plots. The authors observed that some of the subway cars had been rotated during the storm activity; further evidence that shipwreck sites might not always be static structures. A third and final survey was conducted 36 days following the hurricane. A large proportion of the storm induced bedforms had returned to their initial hummocky morphology,
though it was still clear the site had not made a full recovery to the initial pre-hurricane morphology.

Brennan et al. (2016) also utilised a robotic system to perform their MBES surveying at the comparably deep water (depth of approximately 100m) wreck site of the Ereğli E. Here the authors were able to quantify the impact of bottom trawl fishing damage to the ancient shipwreck site by comparing two MBES separated by 11 months. At this site, over a period of just 11 months approximately 15m$^3$ worth of material (both sediment and artefacts) was removed over a 184m$^2$ patch of seafloor. The damage inflicted by bottom trawling dominated any natural current-driven sediment processes and made characterising the modern sedimentary environment a challenge. As a result, the authors were unable to interpret the natural geomorphological conditions of the site. The colourbar used by Brennan et al. (2016) (between ±0.03m was coloured white to indicate no change in relief between the two surveys) implies they were able to achieve survey uncertainty in the region of ±0.02m. Though, marked steps in depth delineating the Remotely Operated Vehicle (ROV) survey tracks suggest that this level of accuracy was not achieved.

Whilst conducting an environmental impact assessment for a proposed wind park development on Arklow Bank a unidentified wooden vessel was discovered. Through the construction of bed-level change plots Quinn and Boland (2010) demonstrated the impacts of what is thought to be anthropogenic activities on this wreck site (the Arklow Bank wreck). Whilst a theoretical vertical accuracy of 0.0175m was quoted, this is likely an ambitious target as this was based on the system specifications alone. This study highlights how much of the MBES time-series data are a by-product of industry lead activities. These data are often non-ideal for use in describing change around wreck sites (in terms of temporal spacing, lack of metadata etc.). Nonetheless, they are some of the few sources of time-series data and are of great value.

Through the review of MBES time-series at wreck sites it has been shown that there is a clear dearth of wreck site bathymetric time-series data; in this study just ten different time-series were identified. These datasets often lacked critical assessment of the impact of environmental conditions on wreck site morphology (many of these case studies have had ulterior motives e.g. assessing MBES uncertainty, mud flow events and illegal activity at wreck sites). Wrecks are often selected for survey when are situated in more extreme environmental settings (e.g. on a sandbank, Stirling Castle; on a mud flow, SS Virginia; exposed to hurricanes, Redbird Reef and SS Yongala; or altered by anthropogenic forcing, Arklow Bank wreck). This is likely to bias the overall analysis of taphonomic processes at wreck sites as these cases do not represent ‘typical’ wreck sites.

The maximum length of the time-series presented in this literature review is 11 years (Burgzand Noord). This time-series is somewhat exceptional; the next longest is just seven years long (SS Yongola). Since some of the processes (e.g. storm events, sandbank
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Migration) operate on a greater than decadal scale it is likely that many of these time-series are too short to capture the full range of sedimentary processes which may occur at the site. Therefore, using these time-series alone without further knowledge of the greater than decadal processes could lead to incorrectly predicting the future trajectory of the site.

Comparison between surveys can be complicated by the differences in the time of year when surveys have been performed e.g. with the SS Virginia wreck the surveys were performed in summer and winter of 2007 and 2009 (Orange and García-garcía, 2009), respectively, and so the presumed inter-annual change could have been masked by a seasonal signal instead.

The only study presented within this paper which collected in situ Meteorological and oceanographic (Metoecean) and geological data was the Redbird Reef site (Trembanis et al., 2013). This study established that regional (10's km) wave buoy data captured the same signal as the in situ devices (linear correlation coefficient, \( r^2 \) of 0.963). Whilst this is useful knowledge for wave data other parameters (tidal currents, sediment composition etc.) may be more spatially variable and so more local data may be required.

Finally, an assessment of the vertical uncertainty of MBES surveys is often lacking and in many of the studies all change is presumed real (Bates et al., 2007; Orange and García-garcía, 2009; Stieglitz and Waterson, 2013). Those that did take into account the vertical uncertainty used a spatially uniform fixed minimum level of detection threshold, which is often overly conservative and can lead to smaller elevation changes being disregarded (Wheaton et al., 2010). In order to correctly identify real change and to produce more plausible and physically meaningful results the uncertainty associated should be determined on a cell-by-cell basis (i.e. spatially variable), this could potentially be performed using Geomorphic Change Detection (GCD) techniques (Wheaton et al., 2010).

The drawback of this method is the minimum requirement for non-sampled MBES data and a full metadata record.

Despite these limitations of using MBES time-series, these studies have successfully quantitatively described centimetric change at wreck sites from a wide range of environments. In many of these studies the primary driver for change has been identified with a good level of confidence. Primarily these studies have focused on the loss of sediment surrounding these wrecks, which could be a result of the choice of sites, since most represent vulnerable and already exposed shipwrecks (the exception being the SS Yongala which underwent no bed-level change). Of the ten sites mentioned in the previous section eight have undergone visible scouring; it is clear that scouring processes are a dominant process at wreck sites. Whilst most authors given in Table 1.1 commented on the presence
of scour at the wreck site in question, the quantification of this scour was mostly a secondary consideration. Arguably, the Quinn and Boland (2010) paper was the most thorough at addressing the processes of scour at a wreck site. This MBES time-series, combined with an understanding of the environmental conditions at the site, provided insight as to the triggers of change at the Arklow Bank wreck site. Utilising this more holistic strategy and with the ever increasing availability of longer and finer resolution MBES surveys the limitations addressed in this section will be reduced.

### 1.2.3.4 Computational Fluid Dynamics

The MBES time-series study on the Arklow Bank wreck site (Quinn and Boland, 2010) was furthered through the use of Computational Fluid Dynamics (CFD) in which the MBES survey data were used as a fixed-bed surface over which flows could be modelled (Smyth and Quinn, 2014). The process of CFD modelling using a fixed MBES bed enables visualisation of the flow pathways at the wreck site at a fixed point in time (i.e. at the time the MBES survey was conducted). How far forwards in time these results can be projected depends on the temporal variability of the site. Since, for example, if the site is exposed to a single storm powerful enough to reconfigure the site morphology, then a reanalysis of the CFD model would be required.

CFD modelling has also been performed around a model shipwreck structure on a flat, immobile, seabed (de Hauteclocque et al., 2007), which had previously been used for physical modelling (Dix et al., 2009; Saunders, 2004; Sullivan, 2008). In this study turbulent kinetic energy was used to estimate the scour pattern. Similarly to the previously conducted physical modelling it was observed that the general shape of the flow around the ship structure was similar to that of a cuboid structure with the same aspect ratio (height:width). However, differences were noted in the position of the maximum wall shear value and shape of the vortex structures.

The results of these CFD models were compared to CFD models of cuboids with the same aspect ratio as the model wreck; from this the effects of the shipwreck structure complexity on scour could be assessed. It was concluded that the flow around a simple cube could be more complex to compute than flow around cuboids or a wreck. Similarly to the work of Smyth and Quinn (2014) these scenarios were only related to a single step in time (i.e. the model was non-coupled). In de Hauteclocque et al. (2007) this time-step was the onset of scour (since the effect of the resultant scour on the flow could not be taken into account).

In the final section of the report de Hauteclocque et al. (2007) presented a full scale comparison of CFD outputs and field data using MBES data from the ‘Unknown wreck’ off
the coast of East Sussex. By using current velocity data collected from an in situ current meter as an input into the model the effects of differing tidal phases on the sedimentary processes were quantified. Only during the middle of the flood tide were current velocities great enough at the site to induce sediment transport and so scouring. When matched to the MBES data the locations of the scour pits matched well with the areas of high turbulent kinetic energy. The validation of the computational model with MBES data demonstrates how computational models still heavily rely on field data for calibration and validation. As such CFD modelling has not emerged as a simple rapid fix for understanding site dynamics.

1.2.3.5 Evaluation of approaches

From this review of approaches to constraining taphonomic processes at wreck sites (summarised in Table 1.2) it is clear that each method has both merits and weaknesses and that no one method is superior.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single survey</td>
<td>• Ability to capture prevailing (net) conditions</td>
<td>• Inability to capture temporal variability</td>
</tr>
<tr>
<td></td>
<td>• Only ever represents a ‘snapshot’ in time</td>
<td>• Multiple possible pathways if tracer objects are not retrievable</td>
</tr>
<tr>
<td>Transportation trials</td>
<td>• Simple methodology</td>
<td>• Limited comparability between different trials</td>
</tr>
<tr>
<td></td>
<td>• Ability to capture prevailing (net) conditions</td>
<td>• Surveys must be of good quality</td>
</tr>
<tr>
<td>Multibeam bathymetry time-series</td>
<td>• Quantitative methodology, allowing comparisons to be made between sites</td>
<td>(i.e. positional accuracy and resolutions of a few 10’s cm)</td>
</tr>
<tr>
<td></td>
<td>• Ability to capture temporal variability</td>
<td>• Survey metadata often lacking/missing</td>
</tr>
<tr>
<td>Computational Fluid Dynamics</td>
<td>• Models can be forced with differing Metocean conditions</td>
<td>• Few existing time-series and often non-ideal survey spacing</td>
</tr>
<tr>
<td></td>
<td>• Turbulent Kinetic Energy can be a proxy for scour</td>
<td>• Few models able to capture the bed-load transport and seabed evolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Models still heavily rely on field data for calibration and validation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Computationally demanding</td>
</tr>
</tbody>
</table>

Focusing this study on multibeam bathymetry time-series alone has the advantage that much of these data have already been collected and so more time can be focused on the processing and analysis of the time-series, rather than in data collection. As demonstrated above there have been few studies utilising multibeam bathymetry time-series
at wreck sites (in this literature review ten were identified). Furthermore, many of these studies focused on wreck sites with atypical conditions; often the driver of the study was that the wreck was already undergoing erosion. Whilst the multibeam bathymetry data used in this study have already been recorded and so the survey spacing cannot be altered, it is important to have an understanding of what processes are being captured between each survey (e.g. storm, tidal, wave, kilometre-scale bank migration). This can be better understood by considering the wreck site as a process-response system which will explained in the following section.

1.2.4 The wreck site as a system

When attempting to determine the long-term stability of a shipwreck site it often helps to consider the site (the wreck and its surrounds) as a process-response system. A process-response system may be either: open, permitting the exchange of energy and materials with the surrounds; closed, permitting only the exchange of energy between the system and its surrounds; or isolated, a system where no interaction with the surroundings across the boundary can occur (these systems are only encountered in the laboratory and not in the field). At any one point in time a collection of values can be used to describe each of the system’s variables (for example, bed-level and the condition of artefacts etc.), this is termed the system state.

In a system there are internal processes, termed ‘scrambling devices’ by Muckelroy (1998) and if the system is open there may also be inputs and outputs of energy and materials (water, sediment, artefacts). The system can undergo modification with time as a result of external disturbance (e.g. excavation, dredging activities, changes in environmental forcing) which then drive change through three mechanisms: i) changes in the inputs/outputs, ii) shifts in the internal organisation of the system itself and iii) through the development of energy or mass stores, which can then lead to lags between disturbance and system response.

The extent to which materials (sediment, water, artefacts) and energy (wave, tidal, storm) at shipwreck sites can freely exchange across system boundaries (i.e. whether wreck sites are open or closed systems) is often debated amongst maritime archaeologists. It’s clear from the studies in section 1.2.3 that there is supporting evidence for shipwrecks to be described both as (near-) closed systems (Muckelroy, 1998, p.268; Hardy, 1990; Church, 2014) and as open systems (Quinn, 2006), as well as being both open (those portions exposed to water) and closed systems (those parts of the wreck that have undergone burial) simultaneously (Gregory, 2012). The degree to which a shipwreck system is an open or closed system will affect how archaeologists interpret the site and the spatial relationships between artefacts and the wreck superstructure, as well as the implementation of resource management techniques.
There are two important factors which need to be taken into consideration when determining whether or not a shipwreck site is an open or closed system, the first was touched upon by Gregory (2012), this is the choice of spatial scale. For example, when considering a shipwreck site at a microscale then bio-chemical deterioration processes are dominant; these are irreversible and will ultimately result in the loss of the shipwreck structure. Whereas, considering sites at a macro/site-scale the site can appear to be undergoing very little or no observable change. Examples where near-zero amounts of energy and material have been exchanged at wreck site scale include the deep-sea wrecks of Robert E. Lee, Gulfpenn and Alcoa Puritan. These sites have only been disturbed by micro-scale bio-chemical deterioration (Church, 2014). At these (near-) closed sites so little exchange of material has occurred that the distribution of the debris can be measured as a function of water depth and vessel size.

Figure 1.3: Schematic of a) Dynamic equilibrium at over long time-scales, b) Steady state equilibrium over medium time-scales and c) Static equilibrium over short time-scales. Adapted from White et al. (1992).

The second factor is the time scale over which the site is considered. Eventually, even if it takes centuries to millennium, all shipwreck sites will degrade to leave no trace on the
seafloor. Over this time scale a wreck is an open system. Whereas, over time scales of minutes to days, the system can be static with no observable loss of material or energy and is effectively closed.

When considering wreck sites as open systems there are further classifications which result from the time scale over which the site is considered. The definitions used here are taken from White et al. (1992) who clearly defined the use of equilibrium nomenclature for the application to a broad range of environmental systems (e.g. catchment basins, glaciers, coastal regions and forests). Over longer time-scales a system can often be considered to be undergoing dynamic equilibrium with a negative trending mean (i.e. where there may be balanced fluctuations but these occur about a mean with a non-repetitive trend) (Figure 1.3a). Whilst, considering a wreck site at a scale of years to decades the system may appear self-regulating, sustaining a steady state equilibrium (i.e. where there may be balanced fluctuations but these occur about a mean that has no trend) (Figure 1.3b). Finally, over a time scale of minutes to days the system appears to be at static equilibrium (i.e. where there is no exchange of materials or energy) (Figure 1.3c).

![Figure 1.4: Schematic of the steady state equilibrium of a hypothetical wreck site over time. Initially the site is not at equilibrium with the surrounding environment, inducing rapid change towards a more stable system (disequilibrium). A certain level of forcing (tidal wave, storm etc.) can be absorbed by the system and it will return to the stable state equilibrium state. Trigger events greater than the threshold which can be absorbed by the system can alter the state of equilibrium so that it fluctuates about a new system state (unstable equilibrium). Adapted from Quinn and Boland (2010).](image)

If it is the case that wreck site systems naturally tend towards stability then the introduction of an external disturbance (e.g. excavation, nearby dredging operations etc.) can have two outcomes: i) the system recovers to the same equilibrium (stable equilibrium) (Figure 1.4 dotted line) or ii) it shifts to a new equilibrium and may be unable to return to the old level of equilibrium (unstable equilibrium) (Figure 1.4 dashed line).
Figure 1.5: Flow diagram of wreck site taphonomic processes featuring a) the wreck b) the sedimentary environment and c) the hydrodynamic environment. Figure reproduced from Ward et al. (1999).

If the system is in some state of equilibrium then this allows us to infer that some self-regulating or negative feedback processes must be operating to sustain the system about some mean trajectory, i.e. if sediment is lost through erosion then this absence of sediment acts to deposit new sediment in its place. If the wreck site is not at a state of equilibrium then the opposite can be inferred, e.g. changes within the site configuration do not act to rebuild or even stabilise (in the case of positive feedback loops).

In system theory initially an immature system will likely be at disequilibrium since negative feedback loops have not yet had time to stabilise the system. In these early-stage systems excess energy is diverted towards the development of a more integrated and efficient functional organisation, i.e. newly formed wrecks will act to settle into a more stable configuration. The epitome of this is the evolution of scour around wrecks. It has been observed that after the initial wrecking process the wreck acts as a bluff obstacle to flow; by doing so it alters the local flow and enhances flow velocities and turbulence, this in turn increases the local sediment transport and leads to scour (Smyth and Quinn, 2014). Once a certain scour depth (the equilibrium scour depth) has been attained the wreck is no longer an obstacle to flow and no further scouring occurs (Whitehouse, 1998).
Chapter 1 Introduction

The idea of using system theory to account for changes at wreck sites is not a new one. Ward et al. (1999) used this technique to create a theoretical model of a wreck site system (Figure 1.5). Whilst this model eloquently captures the inputs and outputs of a wreck system, it somewhat fails to capture the interconnectivity of the sedimentary and hydrodynamic environments.

Because of the potential dynamic or steady state nature of shipwreck sites it is important to recognise that a single time-step survey can only ever describe the site at one point in time, which may, or may not, be representative of the prevailing conditions at the site. By repeating the survey over some period of time the variability at the site can be better constrained. To estimate shipwreck site variability we must first quantify variability at a number of sites covering a range of environmental conditions and account for this variability with an understanding of the Metocean and geological drivers.

1.3 Focusing the problem: research questions

As was introduced in the previous section it is clear that taphonomic processes at wreck sites must be better constrained in order to progress our understanding of the formation and trajectory of these sites and develop better methodologies for managing these invaluable archaeological deposits. To do so three research questions must be addressed:

- How temporally variable are shipwreck site systems?
- How do site conditions affect this variability?
- In terms of a process-response system, how open or closed are wreck site systems?

These questions are deliberately broad in scope and although answering them in this thesis in a globally applicable manner might not be feasible, it is hoped that this large scope will encourage good discussion.

1.4 Aim and objects of thesis

This thesis aims to develop our understanding of historical shipwreck site taphonomy through the use of repeat multibeam bathymetry surveys.

This aim will be addressed through three objectives:

- Develop a systematic and robust methodology for handling environmental data, archaeological data and bathymetric time-series
• Bring together pre-existing bathymetric time-series of wreck sites, expand upon two previously introduced sites (Stirling Castle and Burgzand Noord) and introduce three further case studies (Algerian, Scylla and Richard Montgomery) (locations and dates of surveys shown in Figure 1.6)

• Quantitatively describe the temporal variability of several wreck sites from differing marine environments and account for this through an understanding of the hydrodynamic and geological settings

Figure 1.6: Case study locations and dates of multibeam bathymetry surveys at sites.

1.5 Thesis structure

Following this introductory chapter, Chapter 2 justifies the selection of methods used in processing and analysing multibeam bathymetry data. Alongside this, methods for collating and presenting wreck site environmental data (Metocean and geological) are detailed and these can be used to determine the dominant environmental forces at each site. The final section of this chapter describes the sources of archaeological data used within this thesis and why it is of importance to consider the archaeological significance and management at each wreck site.
Chapter 3 details the site history and management of the primary case study, the SS *Richard Montgomery*. In 1995 a program was initiated to survey the wreck using multibeam bathymetry at a near-annual interval. In this chapter fourteen of these surveys conducted over a seventeen year time period (the longest known MBES time-series of any marine structure in the world) are utilised to demonstrate the value of multibeam bathymetry time-series in quantifying taphonomic processes at a wreck site.

Whilst the *Richard Montgomery* time-series in Chapter 3 represents the longest time-series of any wreck it only informs us about the taphonomic processes of a single wreck site in a single environment. In order to observe whether or not the processes occurring at this site are unique to it, or are more generic and can be applied to other wreck sites, four further sites are analysed in Chapter 4 (*Scylla*, Burgzand Noord, *Stirling Castle*, *Algerian*). Each wreck is presented in order of decreasing similarity when compared to the site of the *Richard Montgomery*. Each wreck case study includes: an environmental background to the site, an examination of the archaeological significance of the site, a summary of the collection of the multibeam bathymetry data, quantification of the bed-level change between surveys and finally an analysis of the causes of taphonomic change at the site. The implications of these findings are discussed both in terms of the heritage management of the site and also for the impact these findings have on the study of scour around submerged marine structures.

Methods for analysing multibeam bathymetry time-series using GCD techniques (the merits of which were briefly highlighted in section 1.2.3.3) are presented in Chapter 5 using the case study of the *Algerian*. These techniques require both the original point spaced MBES file as well as knowledge of the Total Propagated Uncertainty (TPU) of the survey. These techniques could not be performed on the other sites (since data were not supplied in the original raw format files) but by demonstrating the merits of this method it is hoped that this will encourage the use of GCD analysis by others in the future.

Chapter 6 draws together the findings presented in this thesis and provides conclusions as to the value of multi-beam bathymetry time-series of wreck sites and briefly describes a few areas in which future work would be of benefit.
Chapter 2

Data collection and methods

In this chapter methods for constructing Multibeam Echo-Sounder (MBES) time-series and conducting a full investigation of the wreck site’s environmental conditions and archaeological background are described. Firstly, procedures for acquiring Multibeam Echo-Sounder (MBES) data are detailed with a focus on the impact of each input on the total uncertainty of the data. Methods for quantifying this uncertainty are then given. Following this section an assessment is made of the available sources of environmental data (both geological and Meteorological and Oceanographic; Metocean) and of the methods used to analyse these data to provide estimates of seabed conditions (e.g. mobile or non-mobile). Finally, sources of archaeological data describing shipwrecks are evaluated in terms of their usefulness, accessibility and reliability.

2.1 Multibeam Echosounder data

High-resolution (≤1m between soundings) MBES systems are capable of capturing depth soundings at a spatial density sufficient to define a shipwreck and surrounding seabed features. By accurately measuring the delay between transmitting a sound pulse and receiving the return echo from the seafloor (the Two-Way Time; TWT) and having an understanding of the sound velocity properties of the water column, the depth between the MBES transducer head and seafloor can be determined. MBES, unlike older generation singlebeam echosounders, send out a swath of sound to the seafloor resulting in 10’s of depth soundings per ‘ping’ (the number of soundings differs between makes and models of MBES systems). This allows for large areas of the seafloor to be rapidly surveyed to a relatively high resolution.

From this point cloud of positions (x and y) and depth (z) a surface can be constructed known as a Digital Elevation Model (DEM). As one of the research questions of this thesis is to quantify the temporal evolution of shipwreck sites, repeat MBES surveys (time-series) are required. However, before drawing comparisons between MBES surveys, the
set-up of a singular survey must be considered; including the influence of a number of variables (equipment used, environmental conditions, survey setup etc.) on the survey Total Propagated Uncertainty (TPU), resolution and object detection. These factors are of importance when comparing repeat surveys since bed-level change is only statistically significant when it is greater than the TPU of the system.

Key nomenclature used throughout this chapter is shown in Figure 2.1.

2.1.1 Position and depth acquisition

In order to have an understanding of where on the seafloor a sounding has been made it is necessary to accurately record the position of the transducer head. Whilst Global Navigation Satellite System (GNSS) can provide an accurate (≤ metres) x (longitude) and y (latitude) position the vertical accuracy of GNSS is insufficient (2 - 3 times that of horizontal accuracy) to be used alone to describe the altitude of the transducer head. Instead an onboard Inertial Measurement Unit (IMU) senses the roll, pitch, heave and yaw of the vessel (shown in Figure 2.2), which can then be extrapolated to the position
of the transducer head. This constrains the vertical position of the transducer head to within approximately 0.05 - 0.1m (Seibt-Winckler and Riethmüller, 2002).

Figure 2.2: Schematic of typical MBES, IMU and GNSS antenna configuration and principle axes of rotation.

In order to relate the position of the transducer head to the IMU sensor and the GNSS antenna, positional offsets (x, y and z) and rotational offsets (roll, pitch and yaw; determined using a patch test, the methodology of which is touched upon in section 2.1.4.2) between the relative sensors must be accurately recorded. Any time delay (latency) between the sensors must also be quantified. These values, along with the vessel dimensions, are inputs for constructing a vessel configuration file (in CARIS this is the HIPS Vessel File; HVF), used by bathymetric processing software to integrate the data from these three sensors. The integration of the relative positions of the instruments along with Sound Velocity Profile (SVP) and Surface Sound Velocity (SSV) to generate the depth and position of each sounding is shown in Figure 2.3 and 2.4, respectively. In this study CARIS HIPS™version 8.0.0 has been used to process the bathymetric data, the key steps for this are described in the following section.

2.1.2 Collation and formats

The methodology by which raw multibeam data (either in Extended Triton Format (.xtf) or Reson PDS (.pds) format) are processed into an xyz (latitude, longitude and depth) point data file is summarised in Figure 2.5.
Figure 2.3: Contributing measurements towards depth. Modified from Bartlett and Hare (2011).

Figure 2.4: Contributing measurements towards position of depth sounding on seafloor. Modified from Bartlett and Hare (2011).
Chapter 2 Data collection and methods

Three processes within this methodology require subjective user input, cleaning of the: attitude, navigational (auxiliary) and swath data. Data cleaning includes accepting ‘real’ readings and rejecting unwanted or ‘false’ readings. For swath data this is largely performed by assessing whether or not soundings are outliers with regards to neighbouring sounding values either along the same swath or in other overlapping swaths of different lines. Some automation of this process can be included through the use of filters. These allow the operator to reject certain beam numbers (often the outer most beams), soundings below/above a certain depth (i.e. exclude depths above water surface), points with a slope to adjacent soundings above some certain threshold (often just slightly higher than the ‘naturally’ observed angles on the seabed, which is approximately $35^\circ$ for sand; Ernstsen et al., 2006b) and points with a TPU greater than a chosen threshold (often a requirement for data to meet International Hydrographic Organisation (IHO) standards; these are described in section 2.1.5.1). Non-conservative cleaning can remove features such as wrecks due to their steep angles not usually found in natural bed features. Therefore, special attention must be paid when cleaning data where there are known wreck sites.

It is advantageous to collate unprocessed bathymetric data when feasible. This is because once raw data have been processed it is often not possible to retrieve the original data. Therefore, any incorrect inputs (tidal, sound velocity, vessel configuration offsets), any overzealous cleaning (e.g. the removal of depth points relating to a wreck) or interpolation of data to a new resolution, cannot always be undone. Through collating raw datasets it is also possible to maintain consistency between the processing of the datasets; which acts to reduce errors brought in through the use of different methods.

Commonly, raw bathymetric data are unavailable. On these occasions, at the very minimum, the coordinate system and the vertical datum used must be known in order to project the data.

2.1.3 Processing multibeam bathymetry data

2.1.3.1 Point cloud to raster

Once MBES data have been imported into CARIS and have been processed according to the work-flow summarised in Figure 2.5, then the rest of the data manipulation takes place in ESRI® ArcMap (version 10.2.2).

Firstly, data are converted from an ascii (x,y,z) file to a point feature (a geographic representation of an object that is tied to a row in a table). The ‘Average Nearest Neighbour’ tool is run on this point feature. This iteratively calculates the average distances between the nearest neighbour points. This value gives the absolute minimum cell resolution that is possible without introducing interpolation. However, this is not necessarily the resolution at which the surface should be rasterized. Computational demand must also be
taken into account. Therefore, the choice of resolution is a trade-off between loss of information and a decrease in computational demand (this theory is discussed further in section 2.1.4.9).

Once the resolution at which the raster is to be produced has been chosen, the point file is interpolated using point to Triangulated Irregular Network (TIN) and then converted to a raster (the choice of interpolator is discussed in section 2.1.4.10). This raster represents the elevations across the site as a DEM. Surfaces of hillshade, slope and aspect are produced which assist with the qualitative and quantitative description of the site.

2.1.3.2 Comparison between Digital Elevation Models

By extracting values from a DEM along a chosen line, bed-level can be plotted against distance to create a transect through a desired feature. By comparing the same transect
for two or more surveys the bed-level change across a feature can be graphically visualised. Vertical uncertainty can also be shown by the inclusion of error bars on each transect, determining whether or not change between two transects is statistically significant. Whilst transects are ideal for illustrating change across a certain feature, their position is user defined and could be placed such that a certain trend unrepresentative of the overall site is presented. Also, as highlighted by Bolle et al. (2012), scour is an intrinsically 3D problem and cannot be simplified to just 2D. To address this, bed-level change plots showing the change in bed-level at all positions across a surface, are also utilised.

Subtracting the DEM of a less recent bathymetric survey from a DEM of a more recent bathymetric survey creates this bed-level change (erosion-accretion) surface, also termed a DEM of Difference (DoD). On this surface positive values represent a gain in bed-level (accretion) and negative levels represent a loss in bed-level (erosion), with time. From these surfaces transportation pathways of sediment can potentially be inferred.

The overall volume change between two DEM surfaces can also be calculated using Equation 2.1

\[ V = A \sum_{i=1}^{n} \Delta Z_i \]  

(2.1)

Where \( V \) is the volumetric change (m\(^3\)), \( A \) is the area of analysis (m\(^2\)), \( n \) is the number of pixels and \( \Delta Z_i \) is the change in elevation at the pixel \( i \) (m) (Wasklewicz and Scheinert, 2015). Volumetric elevation change distribution can be assessed through the production of histograms of the volume of elevation change. Wheaton (2008) observed that these provided a much better discriminator of the different styles of change (e.g. isolate areas of strong erosion/accretion or more widespread lower levels of erosion/accretion) than areal elevation change distribution. Wheaton (2008) consistently observed that histograms of areal distribution had a single large peak at zero. Whereas, because the volumetric distribution reflects the area multiplied by the magnitude of elevation change towards the tail ends (large negative and large positive values of elevation change) the larger magnitude of change increases the amplitude of the histogram.

Where the DoD methodology comes into difficulty is with the representation of change which is below the detectable threshold, i.e. is smaller than the uncertainty. Uncertainty is inherent to each DEM surface. Therefore, both DEM uncertainty and how this interacts when two surfaces are compared must be constrained.

### 2.1.3.3 Delineating scour pits

In order to quantitatively describe the change in the features of accumulation and scour, a method for defining their spatial extents is required. Scour in marine engineering studies is often described as either local or global, based upon its spatial extent (Sumer et al.,
As Quinn (2006) noted, the description of scour in terms of local and global extent is purely arbitrary and has no quantitative definition. Melling (2014) attempted to create an automated system to define the extent of scour around a monopile. However, he found that no one method worked consistently for each site. Instead he used a combination of bathymetry, slope and hillshade to manually pick out the limits, introducing some level of subjectivity.

Using the definition of Quinn (2006), the scour zone is the area of the seafloor surface which has undergone bed-level change since the introduction of the wreck. This area can, therefore, be described by subtracting a pre-wreck bathymetric layer from a post-wreck bathymetric layer. Pre-wreck bathymetric layers are not available for any of the five case studies presented in this thesis and so a pseudo pre-wreck layer needed to be created. A methodology was developed using windfarm turbine/monopile swath bathymetry data, for which pre- and post-installation surfaces are available (Figure 2.6).

In ArcMap the Hydrology ‘Fill’ tool was applied to the post-installation layer. This hydrography tool fills in any depressions (sinks) in topography. The tool iterates until all sinks are filled, creating a continuous surface for use with other drainage network tools available in the Hydrology package. In this instance it was used to create a pseudo pre-installation layer (Figure 2.6c), which could then be subtracted from the post-installation bathymetry (Figure 2.6b). As the bed-level change values vary according to the depth of the scour holes the difference layer alone cannot be contoured to a set value each time.
Instead the slope tool was applied to the bed-level change layer, which was then contoured for a value of 1 (as this gave the closest result to that of boundary of bed-level change (Figure 2.6d), which then gave us the contour for the scour extent.

The methodology was successful at creating continuous contours for seven out of the ten randomly selected monopile sites. The differences in area and volume for the fill methodology in comparison to the pre- minus post- installation method (Figure 2.6e in comparison to Figure 2.6d) was statistically insignificant (P=0.02). Therefore, this methodology was deemed successful in capturing the scour limits and could then be applied to the wreck site case studies.

2.1.4 Major sources of uncertainty in multibeam echosounder data and products

In the previous sections it has been demonstrated that numerous data inputs (vessel configuration, SVP, tidal elevation etc.) are required to generate depth and position data from raw MBES data. Each one of these inputs has an associated uncertainty that will influence how confident we can be about the final depth and position values. Further uncertainties are then introduced through the gridding and interpolation processes in the creation of depth surfaces; these must also be taken into consideration when estimating the total elevation uncertainty of a survey. In the following sections the greatest causes of uncertainty in MBES surveying will be discussed, in no particular order, as well as methods for minimising these uncertainties in the various inputs. For each cause a recommendation is given as to the best practice in reducing the associated uncertainty.

2.1.4.1 Sonar measurement uncertainty

The quality of the sonar measurement is dependent on the frequency, beam width, pulse length and beam angle of the system. For example, Maleika et al. (2011) observed that when fitting theoretical bottom profiles to Simrad EM3000 data the outer beams (beam angle greater than 45°) had a 50% larger vertical error than the nadir beam (0.028m, in comparison to 0.018m). In good agreement, Lawes (2013), when using a similar method but with a Reson 7125 system, observed a 50% increase in TPU of the outer beams (0.075m, in comparison to 0.05m).

The impact of each of these variables (frequency, beam width, pulse length and beam angle etc.) on TPU is generally well constrained through empirical testing (e.g. Lawes, 2013; Maleika et al., 2011). The complication comes when the user also considers that the actual conditions of the survey will affect the sonar measurement uncertainty, e.g. the seabed reflectivity, complexity, noise in the water column (from bubbles and marine life) etc. (Bartlett and Hare, 2011). IFREMER have developed a Quality Factor (QF) derived
from the acoustic signal to noise ratio of the detection, which captures the quality of the return signal (Lurton and Ladroit, 2010). This QF can then be either applied directly during data editing or as an input parameter to statistical post-processing. However, this method cannot be applied to data that have already been collected since it requires the original return signal of each sounding, which is seldom recorded.

**Recommendation for best practice in minimising uncertainty**
Estimate the quality of the acoustic signal e.g. using the Lurton and Ladroit (2010) QF.

**2.1.4.2 Attitude offsets, accuracy and precision**

When affixing a transducer head to a vessel it is unlikely that the head will be perfectly aligned with the IMU and GNSS sensors. Therefore, any rotational offsets (roll, pitch and yaw) must be quantified and applied during the processing of the bathymetry data. In order to estimate these values a patch test is performed, methodologies for this is are described by Godin (1998) and more recently by Eisenberg *et al.* (2011).

The impact of incorrectly adjusted sensor offsets can be non-trivial. For example, a roll error of 1° on a 50m slant range (equivalent to a 20m water depth and a 120° swath angular sector) will cause a 0.6m difference in the resulting depth. When combined, a yaw misalignment of 2° with a pitch misalignment of 5° introduces an offset of 0.5% of the water depth (in either direction), e.g. in 20m of water depth this would induce a 0.1m error (de Hilster, 2008). By repeating the misalignment measuring de Hilster (2008) observed an average calibration difference of 0.02° for the pitch and roll and 0.19° for the yaw. The roll/pitch offset under this scenario in a water depth of 20m would have an undetectable affect on the depth reading (<0.01m).

When considering attitude data the precision and accuracy of the sensors themselves must be taken into account. Estimated values of accuracy are often quoted by manufacturers, e.g. the R2Sonic I2NS system used in conjunction with a Differential GPS (DGPS) system has an estimated roll and pitch accuracy of 0.03°, a heading accuracy of 0.06° and a heave accuracy of 0.05m. More generally, roll, pitch and heading are accurate to between 0.01° - 0.1° and heave to around 0.05m (CARIS, 2004). The uncertainty of the roll, pitch, heave and heading can now be recorded in real-time by certain systems, e.g. POS/MV, these can then be used directly in the TPU calculation, giving a more realistic estimation of the temporally variable uncertainty than a-priori values (Bartlett and Hare, 2011). Whilst this is not routinely collected, it is increasingly more common and should be encouraged as best practice.

Manufacturer provided values must be used with caution. It is in the manufacturers’ interests to promote the use of their equipment, so these values may represent best case or at the very least the average accuracies of the instruments. During a comparison of
manufacturer-defined uncertainties and observed uncertainties Canter et al. (2005) observed that whilst Root Mean Squared (RMS) values closely resembled the published values, major differences were seen between the published values and the largest values observed during survey (gyro, roll and pitch accuracies were 0.028°, 0.016° and 0.016° larger during surveys than the manufacturer’s provided values, respectively).

**Recommendation for best practice in minimising uncertainty**

Carry out rigorous patch testing and ensure that these data are kept with the MBES data files. Collect real-time attitude sensor uncertainties.

### 2.1.4.3 Position

Similarly to attitude sensor data, the quoted positional accuracy of a GNSS system is likely to represent the best case scenario. During GNSS outages, the system reverts to inertial position only which dramatically decreases the positional accuracy.

Canter et al. (2005) observed that whilst a positional accuracy of 0.5m was given by the manufacturers, their DGPS-IMU system achieved a maximum RMS error of 11.14m. Most DGPS systems have a manufacturers estimated accuracy of between 0.2 - 5m (CARIS, 2004). Whereas, in the Ernstsen et al. (2006a) study the authors achieved an average horizontal precision when using an long range kinematic Global Positioning System (GPS) system of ±0.3m and a minimum of ±0.2m (Ernstsen et al., 2006a).

The vertical accuracy of the position is also a consideration when using Real Time Kinematic (RTK) GPS, since, when using this system, depths are given relative to a true vertical datum. Most RTK systems are capable of achieving horizontal accuracy of 0.01m and vertical accuracies in the region of 0.015m (CARIS, 2004).

**Recommendation for best practice in minimising uncertainty**

Use RTK GPS.

### 2.1.4.4 Vessel configuration and accuracy of measurements

The distance between the IMU, GNSS antenna and transducer can be measured using conventional survey techniques using either a tape measure, laser distancemeter or ideally with a total station. Theoretically the final uncertainties should be in the range of 0.01m and should not considerably contribute towards the total uncertainty budget (Bartlett and Hare, 2011).

If using a total station then over a 5m range an orientation error of 0.25° between any of the IMU, GNSS and transducer offset measurements would result in a 0.02m systematic error in horizontal position (Dix, 2010). Clearly significant offsets can be accumulated through these inputs if methods are not sufficiently robust.
An assessment of the accuracy of the measured offsets can be made relatively easily when several independent sets of measurements are made (e.g. from GNSS antenna to IMU, IMU to transducer, transducer to GNSS). These coordinate variances provide a realistic estimate of the offset uncertainties.

**Recommendation for best practice in minimising uncertainty**

Use a total station to measure offsets and determine standard deviation of calculations.

### 2.1.4.5 Sound velocity measurements

One of the largest contributors to MBES uncertainty is water column sound velocity structure (SVP) and sound velocity at the transducer head (SSV) (Bartlett and Hare, 2011). The Two-Way Time (TWT) of the sound pressure wave is dependent on the sound velocity of the water, which in turn is dependent on the water density and viscosity, the former of which is most influenced by the water salinity, temperature and pressure. The velocity of sound in water increases with increasing temperature, salinity and pressure. To a first approximation for every degree Celsius of temperature increase sound velocity increases by 3m/s, for every one practical salinity unit sound velocity increases by 1.2m/s and for every 30 metres of depth (the predominant control on pressure) sound velocity increases by 0.5m/s (Schmidt et al., 2006). These governing properties vary both temporally and spatially over scales from a single tidal cycle, to seasonal fluctuations. In estuarine environments the variability of these conditions is exacerbated by the influx of fresh water and tidal mixing (Dinn et al., 1995).

As was shown in Figure 2.3, two inputs of sound velocity measurements are required in the collation and processing of multibeam sonar data: i) the velocity of sound at the beam forming head (SSV), used to determine the location from which a return echo has come from, and used in the process of beam forming (the use of constructive and destructive interference to create a narrow beam of sound). ii) profile(s) of sound velocity in the water column, known as SVP. Knowledge of the velocity of sound throughout the water column is used more directly in the depth calculations.

Firstly, the effect of sound velocity on beam forming is considered. In order to determine the location from which a return echo has come, the delay between hydrophone detections is utilised. If the SSV used to calculate this delay is too slow then the calculated delay time will be too long, resulting in a beam fan pattern which is too wide, the inverse of this is also true. The effect of a SSV error is therefore largely dependent on the orientation of the sonar array. Conventionally aligned arrays, installed parallel to the sea floor, result in little error in the nadir beam. The effects of SSV errors on outer beams is exacerbated; SSV values too slow will result in an erroneously wide swath and a deeper measured bathymetry, giving a ‘frown’ appearance to the swath and inversely, for too
fast sound velocities. Because MBES systems do not save wave forms from individual hydrophones, errors in sound velocity used in beam forming cannot be corrected after the data have been collected. Typically SSV at the transducer head is measured to within $\pm 0.02 \text{m/s}$ and is observed at a relatively high sampling rate (1 - 60 Hz) to reduce spatio-temporal effects (Valeport, 2013).

Errors in SVPs, unlike errors in beam forming, can be corrected for in post processing. Since beams angled further from the nadir travel further through the water column an inaccurate SVP will have a larger effect on the outermost beams. If the sound velocity of the water column is underestimated (i.e. the input is slower than the true sound velocity) then the depth of the outermost beams will be calculated to be deeper than their true value, resulting in a ‘frown’ appearance. Whereas, if sound velocity is overestimated (i.e. the input is faster than the true velocity) the depth of the outermost beams will be calculated to be shallower than their true value, giving a ‘smile’ appearance. In estuarine and delta locations, in which many of the case study wrecks are situated, sound velocity can change as much as 20 m/s over less than 10 m of water depth (Cartwright and Hughes Clarke, 2002). If we consider, for example, a water depth of 20 m and a sound velocity of 1500 m/s in the surface 10 m and a sound velocity of 1480 m/s in the lower 10 m of the water column, then an assumption that the water-column is uniform at 1500 m/s would incur a 0.23 m error in the hadir depth reading.

Beaudoin et al. (2009) demonstrated how under sampling SVPs throughout a survey in a relatively heterogeneous waterway (range of 30 m/s between SVPs) can result in an outer beam bias of greater than 0.2 m. Where thermoclines are present and thus a strong gradient in sound velocity with depth, incorrect reconstruction of the SVP (e.g. an offset in the vertical position of the thermocline of just 0.40 m) has been estimated to introduce sounding positional errors on the order of 0.035 m in the horizontal and 0.005 m in the vertical (Stockmann et al., 2009).

**Recommendation for best practice in minimising uncertainty**

Perform a SVP at the very minimum at the start and end of the survey (time interval between SVPs is dependent on the variability of the water column sound velocity).

### 2.1.4.6 Datums

Commonly in the UK depth measurements are provided either relative to Chart Datum (CD) (the lowest depth to which the tide will not frequently fall below, approximately the level of the lowest astronomical tide) or relative to Ordnance Datum (OD). The former varies spatially, but is useful to the maritime community, since it describes the shallowest the sea will be over a certain feature. OD, on the other hand, provides depths relative to a fixed location (in Newlyn, Cornwall). The conversion between the two (OD to CD, or vice versa) can cause the introduction of significant vertical errors (on the order of
10’s centimetres) if incorrectly performed. This issue invoked the creation of the Vertical Offshore Reference Frame (VORF) solution. By relating vertical reference frames to the European Terrestrial Reference Frame conversions between datums can be accurately made (RMS of the order 0.07 - 0.09m within 20km of the coast; Ziebart et al., 2007).

Recommendation for best practice in minimising uncertainty
Ensuring surveys are converted to the same datum using the same method of conversion negates uncertainties associated with changing between datums.

### 2.1.4.7 Tidal correction

When using non-RTK GPS systems then soundings are referenced to the water surface and the contribution of the tide to this depth must be subtracted. In order to do so, tide gauge elevation data are sourced from the nearest available gauge possible. The further the gauge is from the survey site and the larger the tidal range at the site, the larger the error will be introduced through the tidal correction. This error has been reported to be on the order of 0.1m (Schmitt et al., 2008; Smith et al., 2005), but under certain circumstances (when the gauge was 30km from the site) can be up to 0.3m (Schmitt et al., 2008).

Recommendation for best practice in minimising uncertainty
The use of RTK GPS negates the requirement of subtracting the tidal elevation from the depth since soundings are referenced to a true vertical datum. Using such a system results in a total vertical prevision of approximately ±0.02m (Ernstsen et al., 2006a).

### 2.1.4.8 Sea state

During their four year MBES time-series study of a dinghy Ernstsen et al. (2006a) observed that, compared to the other surveys, one in 2004 had a much larger vertical (±0.08m, in comparison to ±0.02m) and horizontal uncertainty (±0.30m, in comparison to ±0.20m). It was noted that during these surveys the range of roll, pitch and heave values were 435%, 567%, and 478% larger, respectively. In other words the sea state was far rougher during the 2004 survey than in the other years. Ernstsen et al. (2006a) concluded that it was the rougher sea state that lead to the larger offsets. Whilst ranges of roll, pitch and heave are useful in describing the sea-state in many datasets these values are not provided. Often survey reports will give a brief description of the sea state conditions and these should be taken into account when analysing the MBES data.

Recommendation for best practice in minimising uncertainty
Surveys should be carried out during calm sea states. Real-time attribute uncertainty should be collected so that the impact of the sea state on the data quality can be constrained.
2.1.4.9 Gridding data

Whilst MBES data are collected in a point cloud format, i.e. have the capability to have spatially concurrent points (points with the same x and y values) with differing elevations, comparison between point cloud data is not straightforward. Often there are difficulties in determining which two points should be compared. Therefore, in the majority of cases, MBES data are converted into a surface or grid (DEM).

Where possible, original point density files should be acquired, as geometric gridding to too coarse a resolution can lead to over smoothing (reduction of maximum amplitude of topographic features, i.e. makes deep scour pits shallower and bedforms/accumulation areas less pronounced) and too fine resolution leads to the creation of data where there are no data points. Ultimately repeat MBES surveys shall be compared by subtracting one surface from another. In order to do so the data must be sampled to the same grid.

Highest useful grid resolution is equal to the spacing of the sounding points. However, the trade-off of high resolution is the size of the data file (the number of values stored increases quadratically with resolution increase). Larger data files are slower to process (e.g. for the purposes of interpolation, data compression, creation of contour maps) (Maleika, 2014). Assuming that each depth uses 4 bytes of data the Table 2.1 details the file size for various grid sizes describing a 1km² area.

<table>
<thead>
<tr>
<th>Grid resolution (m)</th>
<th>No. of point</th>
<th>Size (MB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$10 \times 10^3$</td>
<td>0.04</td>
</tr>
<tr>
<td>5</td>
<td>$40 \times 10^3$</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>$250 \times 10^3$</td>
<td>0.95</td>
</tr>
<tr>
<td>1</td>
<td>$1 \times 10^6$</td>
<td>3.81</td>
</tr>
<tr>
<td>0.5</td>
<td>$4 \times 10^6$</td>
<td>$\approx 15$</td>
</tr>
<tr>
<td>0.25</td>
<td>$16 \times 10^6$</td>
<td>$\approx 61$</td>
</tr>
<tr>
<td>0.1</td>
<td>$100 \times 10^6$</td>
<td>$\approx 381$</td>
</tr>
</tbody>
</table>

When comparing two raster surfaces it is important that each point/cell being compared represent the same area, i.e. the point spacing (resolution) and the point locations are the same. The result of different point spacing is demonstrated in Figure 2.7. In this figure the same transect is described by a high resolution point spacing (a-b) and a lower resolution point spacing (c-d). The resultant sub-sampled surfaces are then subtracted from one another (e), giving a difference in elevation (f). Despite describing the same bathymetry surface there is a difference between the resulting raster surfaces, i.e. if these were two surveys over a site where there had been no temporal change a difference would still be observed in the resultant bed-level change plot. The greatest difference between the two transects is observed along features with steep gradients (Figure 2.7f).
entirely flat surface no difference would be observed. Steep slopes are common to shipwreck sites with associated scour/accumulation features; therefore, it is utmost importance that the point spacing are the same between surfaces being compared.

For example, over an area with a slope of 45°, a reduction in sampling spacing of two times (e.g. comparing a 1m x 1m surface to a 2m by 2m surface) would introduce vertical differences between the two surfaces of 0.25m.

When choosing a resolution at which to compare DEMs it is desirable to optimise the resolution, so that there is ‘sufficient’ accuracy, but reduce as far as possible the amount of data and thus accelerate the processing operations. For Maleika (2014) this was simply a matter of ensuring the model errors did not exceed those required by the IHO to satisfy special order categorisation (International Hydrographic Organisation (IHO), 2008). Where small objects are found on the seabed, such as car wrecks (Maleika, 2014), a high grid resolution is required so that the elevation is described more precisely. For the ‘wreck’ survey case study Maleika (2014) determined an optimum resolution of 0.25m, giving a mean error between the 0.25m grid surface and the original 0.01m grid surface of 0.0089m.
The effects of fixed point spacing but differing location are shown in Figure 2.8. As with the point spacing (Figure 2.7) the offset of the point location has the greatest effect when slopes are being compared (Figure 2.8d). The results of this demonstrate that it is not sufficient to just use the same grid resolution, but that the same grid location must also be used (i.e. the data must be concurrent).

**Recommendation for best practice in minimising uncertainty**

Ensure all surveys are gridded to the same grid. This should not be at a resolution finer than the coarsest survey resolution.

### 2.1.4.10 Interpolation method

The efficacy of an interpolation method is strongly related to the varying characteristics of the terrain, sampling density and interpolation algorithm (Erdogan, 2009). No one interpolation method has been deemed universally superior for the interpolation of MBES data; this is reflected by the wide range of methods still used (Table 2.2). Errors resulting from interpolation can be as small as 0.01m or as large as 0.15m when gridding at a
Table 2.2: Review of interpolation methods used to create DEMs and their recommendations for best results.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Methods</th>
<th>Best Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desmet (1997)</td>
<td>15 methods tested. The spline interpolation yielded the best results as to both precision and shape reliability. However, the study area was extremely smooth.</td>
<td>Spline</td>
</tr>
<tr>
<td>Wheaton (2008)</td>
<td>TIN chosen since kriging interpolation does not work well for coarser resolution datasets often encountered in geostatistics</td>
<td>TIN</td>
</tr>
<tr>
<td>Bater and Coops (2009)</td>
<td>Best results with a minimum of effort when using LiDAR data</td>
<td>Natural Neighbour Algorithm</td>
</tr>
<tr>
<td>Erdogan (2009)</td>
<td>Split-sample, boot-strapping, independent data set. Compared RMS, slope and curvature</td>
<td>Thine Plate Spline</td>
</tr>
<tr>
<td>Maleika et al. (2012)</td>
<td>Scored according to processing time, maximum error, mean error and standard deviation.</td>
<td>Kriging</td>
</tr>
<tr>
<td>Amante (2012)</td>
<td>Split-sample method used to determine the accuracy of three different methods.</td>
<td>Spline</td>
</tr>
<tr>
<td>Johnston (2003)</td>
<td>Comparison made between modelled elevations and measured depths. Comparison between methods of kriging (linear, spherical, exponential, Gaussian and circular weighting scheme) and TIN.</td>
<td>TIN</td>
</tr>
<tr>
<td>Hensleigh (2014)</td>
<td>RMS, mean error, autocorrelation between interpolation error</td>
<td>Inverse Distance Weighting (IDW)</td>
</tr>
</tbody>
</table>

low (15m) resolution (Johnston, 2003). These errors are often inversely related to terrain complexity (Hare et al., 2011). Briefly a few interpolation methods are described here with their relative benefits and disadvantages.

**Inverse Distance Weighting (IDW)** interpolation, which utilises the assumption that points that are close to one another are more alike, has been shown to be less able to model steep surfaces (Erdogan, 2009) and so would be an inappropriate choice for interpolating multibeam bathymetry data over shipwreck sites where steep slopes are common.

Kriging works on two basic assumptions about the surface: that it is continuous and smooth and that neighbouring data points have high correlation with the unknown area. The main disadvantage of kriging is the lengthy processing time for high volume data.

Thin plate spline is an inexact interpolator, i.e. the interpolated surface may not match exactly where it passes through input data. This is a useful trait for data where there is some uncertainty in the point elevations already.
Finally, Triangulated Irregular Network (TIN) uses non-overlapping triangles to create a contiguous surface with each triangular surface represented by a plane. This methodology is advantageous as it can describe the surface at different levels of resolution and is efficient in storing data. The disadvantage of this process is that the discontinuous slopes at the triangle edges can give a non-smooth appearance. This is largely overcome when the TIN is then converted to a raster using linear interpolation, whereby a value is assigned for each cell from the triangular plane at the centre that the cell occupies, the gaps between these values are then linearly interpolated.

There are several methods to assess the efficacy of interpolation techniques:

i. Split-sample (cross-validation): a portion of the data is set aside before the interpolation method is run on the remaining ‘training set’. The unused data are then compared to the interpolated surface.

ii. Bootstrapping: similar to split-sample but only one point is removed before the interpolation, this process is then repeated with a different point excluded each time.

iii. The difference between all the data and interpolated DEM is found.

iv. An independent dataset, at higher point density/accuracy (e.g. Remotely Operated Vehicle (ROV) collected MBES), is compared to the interpolated surface.

The above methods generally generate several descriptive statistics including the minimum, maximum, mean, RMS and standard deviation. Most of these methods estimate the average interpolation error across the survey, which is unlikely to be uniform. Consequently, the spatial variability in interpolation error should also be considered. The processing time should also be taken into account. The only example found of where this has been taken into consideration was in the Maleika et al. (2012) paper. Here, each interpolation method was weighted by its processing time, maximum error, mean error and standard deviation. Unfortunately, Maleika et al. (2012) provided insufficient information on the interpolation methods themselves for this information to be useful.

In this study TIN methods will be been employed. These are both rapid and accurate and are included within Wheaton and colleagues’ Geomorphic Change Detection (GCD) package so can easily be utilised within ArcMap. The error associated with this process is assessed using the interpolation error surface tool. By inputting the point cloud shapefile and DEM the tool quantifies the difference between the surveyed points and the interpolated surface. The output of this tool is a raster surface that represents uncertainty due to the interpolation in the DEM.

Recommendation for best practice in minimising uncertainty
Ensure interpolation method is suited to data (i.e. is fit for the resolution, bathymetric complexity etc.) and that the same methodology is used for each survey.
Table 2.3: Summary of sources and estimates of uncertainty in MBES data.

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
<th>Estimated impact on TPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonar measurement uncertainty</td>
<td>Dependent on both the system (frequency, beam width, pulse length) and the survey conditions (seabed reflectivity, complexity, noise).</td>
<td>In the region of centimetres (calculated using CARIS TPU and a blank vessel file).</td>
</tr>
<tr>
<td>Attitude offsets, accuracy and precision</td>
<td>Roll, pitch, heave and yaw are used to determine both the depth of the measurement and its position on the seafloor.</td>
<td>Misalignment of the instrument should have negligible impacts on the TPU when correctly surveyed in.</td>
</tr>
<tr>
<td>Position</td>
<td>Recorded by the GNSS antenna and then converted to the position of the transducer head.</td>
<td>Heavily dependent on the choice of GNSS system (e.g. stand-alone, DGPS, RTK etc.). THU in the region of 10’s centimetres.</td>
</tr>
<tr>
<td>Vessel configuration and accuracy of measurements</td>
<td>Used to convert the attitude measurements and position relative to the transducer head.</td>
<td>Variable between setups and techniques used to measure offsets (e.g. tape vs. total station). In the region of 0.01m.</td>
</tr>
<tr>
<td>Sound velocity measurements</td>
<td>Used both during acquisition, in beam-forming and as well as to convert the velocity of signal return to a value of depth.</td>
<td>Potentially in the region of 10’s of centimetres.</td>
</tr>
<tr>
<td>Datums</td>
<td>To allow for comparisons between surveys the depths must be given relative to the same datum. Conversion between datums can introduce errors.</td>
<td>For the conversion of OD to CD using VORF, RMS is on the order of 0.07 - 0.09m. No error if same datum and methods for conversion.</td>
</tr>
<tr>
<td>Tidal correction</td>
<td>In order to convert the measured depth to a set datum the tidal contribution must be subtracted (except in the case of RTK).</td>
<td>Dependent on the distance from the gauge and the tidal range at the site. TVU can be in the region of 10’s centimetres.</td>
</tr>
<tr>
<td>Sea state</td>
<td>Precision has been observed to decrease with increased ship attitude.</td>
<td>Ernstsen et al. (2006a) observed a THU 4 times larger and THU 1.5 times larger during rough sea state.</td>
</tr>
<tr>
<td>Gridding data</td>
<td>Through gridding, data can be created (interpolation) and lost (if too coarse resolution used).</td>
<td>If correctly performed TPU in the region of centimetres (Maleika, 2014).</td>
</tr>
<tr>
<td>Interpolation method</td>
<td>The choice of method can vary the quality of the output.</td>
<td>In the region of centimetres (Hensleigh, 2014).</td>
</tr>
</tbody>
</table>
2.1.5 Methods for estimating multibeam echosounder uncertainty

In order to determine what values of bed-level change are statistically significant the uncertainty of the surveys being compared must be known. It has been demonstrated in the previous section and summarised in Table 2.3, that MBES depth is a complex product of many values from different instruments, each with its own associated uncertainty. In an ideal situation, for each MBES survey, sufficient survey metadata are provided so that the TPU for each depth reading can be calculated (Method 1 below). However, this is rarely the case. Instead the TPU must be estimated using one or more of the following methods (Methods 2 to 8).

2.1.5.1 Method 1 – Combined uncertainty

Perhaps the most comprehensive method for determining the TPU of a survey is to quantify the uncertainty inherent in each piece of equipment (navigation, gyro, heave, pitch, roll, tide error, sound velocity error, latency error, sensor offset error and individual sonar model characteristics) and how those uncertainties are inter-related, often through the Root Sum Squared (RSS). The TPU includes estimates of both the TVU and THU.

In Caris instrumental uncertainty data are stored in two different files: the HIPS Vessel File (HVF) and the Device Model. From this the THU and the TVU can be estimated. This methodology can be performed within CARIS and produces a Combined Uncertainty Bathymetric Estimator (CUBE) surface and so gives an estimation of the spatially variable uncertainty. This method heavily relies on the uncertainty estimates provided by instrument manufacturers, the reliability of which is often questioned (Canter et al., 2005).

In version 8.1.14 of CARIS HIPS™ a TPU Analysis tool was introduced. This allows the user to view the breakdown the uncertainty into its contributions from GPS, sonar (angle and range), sound velocity, heading, IMU alignment, roll, heave and pitch (Foster et al., 2014). As this version of Caris was only made available in 2013 the results of this method are not shown here.

Guidelines for acceptable ranges of TVU and THU have been provided by the IHO (International Hydrographic Organisation (IHO), 2008)(Table 2.4). These are dependent on the ‘order’ of the survey, which is usually specified by the contractor and largely influenced by area in which the survey is conducted (harbour, coastal, offshore etc.). To qualify for special order the THU must be smaller than 2m and the TVU (where survey depth is 20m) must be below 0.3m. Certain wreck site surveys may be provided with a description to which order has been achieved, this can then be used to estimate the TVU and THU of the data.
Table 2.4: Maximum acceptable THU and TVU for IHO specifications. Based on a water depth of 20m.

<table>
<thead>
<tr>
<th>Order</th>
<th>THU (m)</th>
<th>TVU (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special order</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>Order 1a</td>
<td>6</td>
<td>0.6</td>
</tr>
<tr>
<td>Order 1b</td>
<td>6</td>
<td>0.6</td>
</tr>
<tr>
<td>Order 2</td>
<td>7</td>
<td>1.1</td>
</tr>
</tbody>
</table>

One of the drawbacks of using the combined uncertainty as an assessment of the uncertainty is that it does not include certain errors such as: refraction, vessel squat and water level errors. It is also unable to provide information on the survey seafloor coverage and target detection capabilities and relies heavily on manufactures’ provided accuracies.

2.1.5.2 Method 2 – Common benchmark

By resurveying an immobile feature (e.g. an immobile shipwreck or other anthropogenic feature) or area of seabed (e.g. an area of bedrock) and observing the difference between the two survey’ surfaces some assessment can be made as to the vertical and horizontal uncertainty of the survey. This methodology has been employed by Schmitt et al. (2008), Stockmann et al. (2009) and Ernstsen et al. (2006a), amongst others.

The first caveat of this methodology is that the feature must have remained in the same position between surveys, i.e. it must be an immobile object/surface. Even surfaces thought to be stable such as bedrock can still accumulate sediment or biological growth sufficient to alter the vertical position of the seabed (Schmitt et al., 2008).

Secondly, this methodology can only assess the precision of the survey. The accuracy of the readings is still unknown as the measurements are not independent of each another.

This methodology is also sometimes used to correct surveys where there is believed to be a fixed vertical or horizontal offset (bias). In doing so surveys are registered and shifted to align better with some other survey by assuming elevation differences are near-zero over some particular feature (Smith et al., 2005). Following this method the assumption is made that the feature has remained stable in its vertical position between surveys and that there is a constant offset across the survey. This method is less effective in areas where the bed is highly mobile e.g. in a region of sandbanks and where the bed-level is shifting (e.g. due to a change in the area’s tidal regime or subsidence). As well as using areas of seabed to register surveys it is also common practice to use manmade features, such as shipwrecks, as fixed features (Bates et al., 2011; Ernstsen et al., 2006a). Again, caution must be practised when using manmade objects as fixed points since their immobility cannot always be confirmed.
2.1.5.3 Method 3 – Repeat survey

The survey is repeated with a minimal temporal spacing (e.g. a few hours). The seabed is assumed to be stable over this time-scale and any change is assumed to represent uncertainty (Herzog and Bradshaw, 2005). Change can be assessed through comparison of: i) the maximum absolute elevation difference in each cell, ii) the standard deviation between each cell and iii) the average of the DEM of difference. Wheaton (2008) observed a mean absolute elevation difference between two repeat surveys of 0.048m, despite the same system being used.

If the same tide gauge and vessel offsets are used then this reduces the number of devices for which the uncertainty is being calculated. Ideally this methodology would require full demobilisation and re-affixing the devices so that errors in measured instrument offset can be estimated. Again, similarly to method 2, this only gives an estimate of the precision of the survey and not the accuracy.

2.1.5.4 Method 4 – Repeat tracks

By assessing difference in elevation between repeat tracks of the same survey, where the swaths overlap, the precision of the system can be examined. This methodology shares the same advantages and disadvantages as method 3, with the exception that the equipment cannot be demobilised during the survey and that the raw data file (or line by line date files) must be accessible. Depending on how close together in time the lines were taken will also influence how well they capture any time-variable uncertainties (sound velocity, tidal elevation etc.).

This methodology can be furthered through the creation of a reference surface from only the inner (or outer) beams and then comparing this surface with repeat tracks (Whittaker et al., 2011). As expected this method demonstrates the increase in uncertainty in the outer beams. But, more interestingly, identified the trenching artefacts of the nadir depth readings due to soft bottom penetration, frequently these were larger than the IHO order 1a specifications.

2.1.5.5 Method 5 – Independent dataset

The MBES survey is compared to a more accurate (an assessment of whether or not another system is more accurate would largely have to be based on the provided system specifications) and independent dataset (e.g. a more accurate MBES, Autonomous Underwater Vehicle; AUV or Light Detection and Ranging; LiDAR) this is then treated as the true depth. The residuals between the MBES and other survey can then be calculated, giving an estimate of the uncertainty of the MBES data.
Debese et al. (2012) demonstrated this methodology at an inter-tidal site through the use of four different MBES systems and a reference surface obtained from a 3D terrestrial laser scanner. This methodology identified systematic errors in all four of the MBES systems, but was unable to identify the nature of the error. Unlike most of the other methods listed here, this methodology provides an estimate of the survey accuracy as well as the precision.

2.1.5.6 Method 6 – Beam-to-beam comparison

By fitting a polynomial for each ping line (perpendicular to the trackline) and measuring the difference between points and this polynomial an estimate of the device readout error can be made (this assessment does not include roll/pitch/heave offsets) (Maleika, 2012). This error can then be related to beam angle and depth.

Building on the methodology of Maleika (2012), Lawes (2013), using the assumptions that the seabed is locally homogeneous for short along-track distances and that each beam is independent, assessed the vertical TPU of MBES by analysing the median and maximum variance across sets of consecutive pings.

Again the method can only give an assessment of the precision and not the accuracy of the data.

2.1.5.7 Method 7 – Detrended standard deviation

This methodology relies on the assumption that there are small elevation variabilities across small spatial scales (10’s centimetres). By calculating the locally detrended standard deviation based on the elevation values the Topographic Point Cloud Analysis Toolkit (ToPCAT) roughness tool gives a measure of the uncertainty (Rychkov et al., 2012), but not the accuracy.

2.1.5.8 Method 8 – Coincident points

Expanding upon method 7, by comparing only those values where the x and y position are the same (coincident points), this method does not rely on there being minimal elevation variability (Kasprak et al., 2014). In order to perform this methodology the raw point spacing data are required and these must have been recorded to a fairly high point density in order to have coincident points. By comparing coincident points from lines, time variable uncertainties can be captured. This methodology also gives an estimation of the survey precision, not accuracy.

Whilst 8 different methods for assessing the uncertainty of MBES data have been identified and described in this section (summarised in Table 2.5 and Table 2.6), it is clear
Table 2.5: Data requirements for method for estimating uncertainty of MBES data.

<table>
<thead>
<tr>
<th></th>
<th>Method 1</th>
<th>Method 2</th>
<th>Method 3</th>
<th>Method 4</th>
<th>Method 5</th>
<th>Method 6</th>
<th>Method 7</th>
<th>Method 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw dataset (e.g. xtf, pds etc.)</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Fixed feature (e.g. bedrock)</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Minimal repeat spacing</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Full survey metadata</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Independent dataset</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>High, non-gridded, point density</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 2.6: Output of methods for estimating vertical uncertainty of MBES data. Method 1 can provide temporally variable error when using real-time attitude accuracy. Method 1 can give estimation of device readout error when a quality factor is provided (Lurton and Ladroit, 2010)

<table>
<thead>
<tr>
<th></th>
<th>Method 1</th>
<th>Method 2</th>
<th>Method 3</th>
<th>Method 4</th>
<th>Method 5</th>
<th>Method 6</th>
<th>Method 7</th>
<th>Method 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Accuracy</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Temporally variable errors</td>
<td>✓¹</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Temporally fixed errors (bias)</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Device readout error</td>
<td>✓²</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Table 2.7: Availability of requirements, given in Table 2.5, for the five wreck site case studies.\textsuperscript{1}For 2005-2012 only.\textsuperscript{2}For 2006-2014 only.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Richard Montgomery</th>
<th>Stirling Castle</th>
<th>Burgzand Noord</th>
<th>Algerian</th>
<th>Scylla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw dataset</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Fixed feature (e.g. bedrock)</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Minimal repeat spacing</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Full survey metadata</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Independent dataset</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>High, non-gridded, point density</td>
<td>✓\textsuperscript{1}</td>
<td>×</td>
<td>✓\textsuperscript{2}</td>
<td>✓</td>
<td>×</td>
</tr>
</tbody>
</table>

Table 2.8: Possible methods for calculating the survey uncertainty for the six wreck site case studies.\textsuperscript{1}1 day repeat interval.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Richard Montgomery</th>
<th>Stirling Castle</th>
<th>Burgzand Noord</th>
<th>Algerian</th>
<th>Scylla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Method 2</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Method 3</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓\textsuperscript{1}</td>
<td>×</td>
</tr>
<tr>
<td>Method 4</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Method 5</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Method 6</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Method 7</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Method 8</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
</tbody>
</table>

from Table 2.7 and Table 2.8 that few of the five wreck site time-series have the necessary data in order to allow for these methods to be used, a common problem with using existing datasets. Method 2 (Common benchmark) is fairly straightforward and simple and has already been applied to the Stirling Castle data. It will therefore be used at the remaining four sites where possible.

2.1.5.9 Impact of uncertainty on DoDs

DEM quality is a function of survey point quality, sampling strategy, surface composition, topographic complexity and interpolation methods. How large this uncertainty is will affect the minimum level of detection. Uncertainty is propagated following the equation:
\[
\delta u_{\text{DoD}} = \sqrt{\pm(u_{\text{survey1}})^2 + \pm(u_{\text{survey2}})^2}
\]  
\hspace{1cm} (2.2)

where \(u_{\text{survey1}}\) and \(u_{\text{survey2}}\) are the vertical uncertainties of two DEMs and \(\delta u_{\text{DoD}}\) is the propagated uncertainty for the DoD. For example, if survey 1 had an uncertainty of \(\pm 0.2m\) and survey 2 had an uncertainty of \(\pm 0.3m\) then the resultant DoD would have a vertical uncertainty of \(\pm 0.36m\). This value is also referred to as the minimum level of
detection threshold (LoD_{min}), i.e. all change within \(\pm 0.36m\) would be deemed to be undetectable and would therefore be excluded for the analysis of the DoD.

Determining this value of LoD_{min} is no easy task. Whilst methods for estimating uncertainty have been presented here, these values alone do not necessarily capture the total uncertainty of the DEM produced from the MBES data. This is because the uncertainty of the DEM is also influenced by sampling strategy, surface composition, topographic complexity and interpolation methods.

Fixed minimum level of detection thresholds have often been somewhat arbitrarily derived, frequently without justification (e.g. Manders, 2009; van den Eynde et al., 2013). The use of a fixed, spatially uniform LoD_{min} often results in the over conservative removal of data where the vertical uncertainty is small (e.g. flat areas with a high survey point density) and a liberal accommodation of data where vertical uncertainty is high (e.g. areas with large slopes and low survey point density). To address this issue Wheaton et al. (2010) exploited the relationship that DEM vertical uncertainty exhibits patterns in its spatial variability that are coherent and predictable. Through this he developed a software package, GCD, which estimates vertical uncertainty through two different methods: i) spatially variable uncertainty quantification and ii) spatially coherent units. Details of these methods are given in Wheaton (2008) and Wheaton et al. (2010). By combining these methods the GCD software produces DoD which are more plausible and physically meaningful. These methods will be applied to the Algerian in Chapter 5.

### 2.1.6 Other Considerations for multibeam echosounder data

#### 2.1.6.1 Survey resolution

Rather than measuring the depth of a single point on the seafloor each MBES beam insonifies a small patch of the seafloor and thus the return represents the average depth of a certain area, the beam footprint. The size of the beam footprint can be described by the across-track width and the along-track width. Atop this, when beam footprints do not overlap, the resolution of the survey is dependent on the spacing between these patches of insonified seafloor. The larger the spacing between these measurements, both in the along-track and across-track directions, the lower the resolution of the bathymetry data. The equations given here come from Hare (2001).
Chapter 2 Data collection and methods

The across-track resolution is a function of the number of beams, angular sector, beamwidth and beam spacing. As the beams get closer to the nadir (the beam directly below the transducer) the beamwidth and thus the beam footprint decrease in size so that a smaller area of the seafloor is sonified. Equation 2.3 gives the optimal across-track resolution.

\[ y_{\text{res}} = d \left[ \tan \left( \theta - s_{ps} + \frac{\psi_y}{2} \right) - \tan \left( \theta - s_{ps} - \frac{\psi_y}{2} \right) \right] \] (2.3)

where \( \psi_y \) is the across-track beamwidth, \( s_{ps} \) is the seafloor slope in the port-starboard direction, \( d \) is the depth and \( \theta \) is the beam angle.

In the worst case scenario the across-track resolution is equal to the beamwidth projected on the seafloor, Equation 2.4.

\[ \delta y = \frac{H \theta_R}{\cos^2 \theta} \] (2.4)

Where \( H \) is the water depth, \( \theta_R \) is the transversal beam width. In practice the across-track resolution will be a value between the value derived from Equation 2.4 and Equation 2.3.

The along-track resolution is controlled by the vessel speed and pulse rate. If the vessel’s speed increases and the time between ‘pings’ remains the same then the spacing between each ‘ping’ will increase resulting in a decrease in the along-track resolution. Optimally the ping repetition frequency consists in transmitting a signal as soon as the previous signal has been received giving Equation 2.5.

\[
\text{Along-track spacing} = \frac{\text{SOG}}{\min \left[ \text{maximum ping rate}, \frac{1}{\text{compute time} \times (\frac{2 \text{max range}}{c})} \right]} \] (2.5)

in which Speed Over Ground (SOG) is the ship speed over ground, \( r \) is the longest range and \( c \) is the sound speed in water. Spacing can be simplified to SOG divided by the ping rate. However, a more robust method is to use the minimum of either the maximum ping rate or sounder specified maximum ping rate (the TWT of the longest range in any one ping plus and estimate of the computation time for processing each ping, approximately 20%).

The size of the beam footprint on the seafloor must also be considered (Equation 2.6).

\[ x_{\text{res}} = \frac{2r \tan \left( \frac{\psi_x}{2} \right)}{\cos (s_{fa})} \] (2.6)

where \( x_{\text{res}} \) is the along-track resolution (m), \( r \) is range from the transducer to the seafloor (m), \( \psi_x \) is the along-track beamwidth (°), \( s_{fa} \) is the seafloor slope in the fore-aft direction (°).
In practice the along-track resolution will be somewhere in-between the values calculated using Equation 2.5 and Equation 2.6.

Whilst these four equations give the theoretical resolution, in practice overlapping swaths and seabed complexity alter the resolution. To achieve a higher grid resolution Maleika (2014) recommended surveying the site more than once (over a short period of time) to increase the measurement point density. However, the repetition of survey lines can increase error associated with temporally variable parameters, e.g. tidal elevations and sound velocity and can lead to the blurring of the depth surface. Furthermore, as described above, once soundings are as close together as the size of their beam footprints then further increasing the density of soundings will not increase the resolvability of objects on the seafloor.

### 2.1.6.2 Object detection

In order to detect features within a MBES survey, such as archaeological artefacts, the resolution of the data must be sufficient to isolate the feature from the background noise and any natural seabed features. Commonly, based upon user interpretability, a minimum requirement of three points to detect a target is used (Wu et al., 2013). If this is the case, the object dimension must be three times the length of the beam spacing on the seafloor and the beam footprints must not overlap considerably.

Bates et al. (2011) were able to detect features down to a size of 0.4m × 0.5m. Though their data had an along-track resolution of 0.005m. Bates et al. (2011) stipulated that they would be able to resolve objects as small as 0.015m (three times the along-track resolution).

Object detection is both a function of the horizontal \((x,y)\) size of the object and the horizontal resolution of the survey as well as the height \((z)\) of the object and the vertical resolution of the survey. However, since the vertical resolution of MBES systems is two orders better than horizontal resolution (Hare, 2001) the vertical resolution is rarely a limiting factor for object detection so is not considered here.

The horizontal detection threshold for multibeam is three times the maximum of the distances calculated using Equation 2.3 to Equation 2.6 (Galway and Hughes-clarke, 2000; Hare, 2001):

For example using a sound velocity of 1500m/s, a seafloor slope of 10° (in both port-starboard and fore-aft direction), a water depth of 20m, a beamwidth of 1.5° (in both along track and across track), a ship speed of 1.5m/s, a swath of 120° made up of 256 beams then we would expected the following to be true:

\[
\begin{align*}
\text{i. } x_{\text{res}} &= 2 \times 20 \times \tan(1.5/2) / \cos(10) = 0.5m
\end{align*}
\]
ii. Spacing = 1.5/(1/1.2 \times (2\times40/1500) = 0.1m

iii. $\delta \theta = \theta_{256} - \theta_{255} = 0.65m$

iv. $y_{res} = 20(tan(60-10+1.5/2) - tan(60-10-1.5/2)) = 1.3m$

Therefore, in this simple example, the limiting factor on point resolution is the across track beam footprint (1.3m in the across track direction). In this example an object on the seafloor with dimensions greater than 3.9m should be detectable.

As well as the sounding density and the size of the beam footprint, the raster resolution will also impact upon the resolvability of seafloor targets. Empirically, Plets et al. (2011) observed that the shipwreck of the SFW William Mannel (of dimensions 53m x 11m x 0.5m) was visible when the data were gridded to 2m raster resolution, but not when gridded to 5m, as, at this resolution, the feature was then interpreted as a continuation of the bedform field to the north-east.

2.2 Environmental Data

In order to make an assessment of the effects of the site-specific marine environmental conditions on the taphonomic processes occurring at a wreck site, the geomorphological, geological, wave, tidal conditions and storm history of the site must be constrained. In this section sources of these data are discussed and their relative merits compared. Often a single dataset is not sufficient and a series of sources must be used in tangent to quantify the site specific environmental conditions.

2.2.1 Geomorphology

Often wreck MBES surveys have a relatively limited spatial coverage ($\approx100$’s m by $\approx100$’s m). However, an understanding of the gross morphology of the area is paramount to constraining the wreck site conditions. Natural features such as banks and headlands can alter the flow around a site and shelter it from storm events. Slope, which can be quantified using large-scale bathymetry surfaces, is a controlling factor in wreck site taphonomic evolution (Muckelroy, 1977) and is a controlling variable in the calculation of threshold bed shear-stress (Soulsby, 1997, p.107). Therefore, it is advantageous to obtain bathymetry data for the wider surrounding area of the wreck site.

2.2.1.1 Data processing

Similar processing methods are performed on large scale bathymetry as with the site MBES data, e.g. the data need to be converted from point cloud to raster (though these
Table 2.9: Sources of geomorphological data for the UK, their location, parameters, coverage and comments on their disadvantages and advantages.

<table>
<thead>
<tr>
<th>Source</th>
<th>Parameter</th>
<th>Coverage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>INSPIRE portal and MEDIN</td>
<td>Bathymetry</td>
<td>Near UK wide</td>
<td>Depths given relative to CD. Most data at 1m spacing. Higher resolution data available on request.</td>
</tr>
<tr>
<td>Bathymetry Data Archive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port authority</td>
<td>Bathymetry</td>
<td>Port licensed area</td>
<td>Often not published, but available on request.</td>
</tr>
<tr>
<td>Admiralty charts</td>
<td>Features and low resolution bathymetry.</td>
<td>UK wide</td>
<td>Through importation into GIS software and georectification a comparison can be made between charts with time.</td>
</tr>
</tbody>
</table>

are normally provided pre-gridded). Using ArcMap tools surfaces of slope, aspect and hillshade can be produced. This give both qualitative and quantitative description of the overall morphology of the area. The sea horizon (the sector of open water for a given distance; Muckelroy, 1977) can be determined if the spatial coverage is sufficient. Locations of features such as headlands, sandbanks and dredged channels should be noted. These surfaces can also be contoured and compared to historical charts (the method for which is provided in Section 2.2.9) to assess change over longer time-scales.

2.2.2 Geology

The availability and type of surficial sediments have a strong control on the sedimentary processes at the site. If no unconsolidated sediments are available, e.g. the wreck is on an exposed rock surface, then no scouring and no burial will occur. The grain size of the material will influence the threshold for transport, with smaller grains being transported under lower velocities than larger grains, until a point at which grains behave cohesively and erodibility then decreases with decreasing grain size (Soulsby, 1997). Non-cohesive, smaller grain sizes have been observed to scour at a faster rate and to a deeper depth (Whitehouse, 2006). The structure of the sediment layers below the surficial sediment layer also regulates the depth to which scouring can occur. Scouring can become supply limited if a resistant layer is met (Whitehouse, 1998, p117).

2.2.2.1 Useful information

The key location-specific data needed to assess the relevant geological parameters that might affect a site are therefore: the nature of the surficial sediments (sorting, median
Table 2.10: Sources of geological data, their location, parameters, coverage and comments on their disadvantages and advantages.

<table>
<thead>
<tr>
<th>Source</th>
<th>Parameters</th>
<th>Coverage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGS Offshore Geodindex of Open Geospatial Consortium Web Map Services</td>
<td>Grab, borehole, drill, dredge and core samples</td>
<td>UK wide</td>
<td>Often poor spatial resolution of samples</td>
</tr>
<tr>
<td>Port Authorities</td>
<td>Varied</td>
<td>Varied</td>
<td></td>
</tr>
<tr>
<td>Industry led projects</td>
<td>Varied</td>
<td>Varied</td>
<td></td>
</tr>
<tr>
<td>Academic papers</td>
<td>Varied</td>
<td>Varied</td>
<td></td>
</tr>
<tr>
<td>MBES</td>
<td>Mobility of seabed can be observed, from which one can infer whether or not the sediment is unconsolidated</td>
<td></td>
<td>Methods for extracting bedload transport from this source are discussed in a later section</td>
</tr>
<tr>
<td>Admiralty charts</td>
<td>Description of seabed type</td>
<td>UK wide</td>
<td>Only qualitative descriptors</td>
</tr>
<tr>
<td>JNCC UKSeaMap</td>
<td>5 categories based on folk triagon</td>
<td>UK wide</td>
<td>Shapefile</td>
</tr>
</tbody>
</table>

Grain diameter, spatial variability, depth); and the bulk properties of the underlying layers (d50, depths, consolidation). The surface sediment properties, are likely to be both temporally and spatially variable, and as such metadata in the form of depth of sample, location and date of sampling are also needed.

### 2.2.3 Tidal currents

Tidal currents are one of the main drivers of sediment transport at UK wreck sites, reaching in excess of 4 m/s (ABPmer, 2008). As well as their ability to mobilise sediments, the asymmetry of tidal currents can also alter the rate of evolution of scour around marine structures and create asymmetrical morphological structures to the flood and ebb side of the structure (Porter et al., 2014). Ideally, in order to capture a range of tidal conditions (spring-neap cycle), tidal stream and current data should be measured for a period of at least 30 days (International Hydrographic Organisation (IHO), 2008). The presentation of these tidal data as polar plots showing both the current velocity and directionality with time before/after high water, allows any asymmetry in the strength or directionality tidal current to be observed. The most important parameters relating to site stability are flow velocity, direction and tidal elevation. Sources of tidal data are given in Table 2.11.
Table 2.11: Sources of tidal data, their location, parameters, coverage and comments on their disadvantages and advantages.

<table>
<thead>
<tr>
<th>Source</th>
<th>Parameters</th>
<th>Coverage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Diamond, UKHO Admiralty charts</td>
<td>Speed and direction of tidal flow for upper 10m of water column over HW-LW cycle and for both spring and neap tides.</td>
<td>UK wide coverage</td>
<td>Accessible via UKHO charts, covers a whole HW/LW cycle, direction as well as strength. Very short observation period (min. 12 hours). Therefore, only encapsulate most basic tidal constituents. Also only represents upper 10m of flow.</td>
</tr>
<tr>
<td>UK Marine Renewable Energy Resource Atlas</td>
<td>Spring and Neap peak flow. Annual % exceedance of 1m/s and 2m/s. Spring and Neap range. Tidal ellipses.</td>
<td>UK Renewable Energy Zone (REZ) (within 200m depth contour)</td>
<td>UK wide coverage, GIS shapefile, M2 major axis orientation, parameters given for mean depth. Coarse resolution (1.5 x 1.5km areas). Model data might not account for local variations.</td>
</tr>
<tr>
<td>BODC</td>
<td>Eulerian current meter data speed and distribution</td>
<td>UK wide</td>
<td>Multi-depth. Very sparse spatial distribution, often of unknown quality.</td>
</tr>
</tbody>
</table>

2.2.4 Wave climate

Wave conditions can vary enormously site-to-site, with factors such as exposure, fetch and water depth strongly influencing the dominance of wave induced transport on the overall site taphonomic processes. However, wave influence can be instrumental in sediment transport processes at shallower sites.

In order to make an assessment of the wave climate at a site, time-series of the significant wave height ($H_s$), directionality and wave period ($T_p$) should be sourced using one or more of the data depositories given in Table 2.12.

2.2.4.1 Processing and displaying wave data

Commonly wave data are provided at intervals of 20 minutes up to every 3 hours. Most sources provide average wave period ($T$), dominant wave period ($T_p$) and significant wave-height ($H_s$). Directional wave buoys also give dominant wave direction. Wave data are
Table 2.12: Sources of wave data including parameters, coverage and comments on their disadvantages and advantages.

<table>
<thead>
<tr>
<th>Source</th>
<th>Parameters</th>
<th>Coverage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Coastal Observatory (CCO)</td>
<td>$H_{m0}$, $H_{max}$, $T_p$, $T_z$, Dir, spread and SST</td>
<td>36 buoys UK wide</td>
<td>Mostly south coast sites. Reports of annual statistics of sites also available</td>
</tr>
<tr>
<td>CEFAS wavenet</td>
<td>$H_{m0}$, $H_{max}$, $T_p$, $T_z$, Dir, spread and SST</td>
<td>64 buoys UK wide</td>
<td>Both historical and current buoy data available</td>
</tr>
</tbody>
</table>

provided already quality controlled and data with dubious quality were excluded from further analysis. These data are then imported into MATLAB for analysis and the creation of rose plot and time-series figures.

In order to identify storms a peaks-over-threshold method is used. An empirically derived threshold is used and is based on an exceedance level of 0.05 - 0.1% over a time-series of ideally at least 5 years (Bradbury et al., 2007). Using this method creates a record of storm intensity and frequency of major storms.

Within the 2014 wave report produced by the CCO the significant wave height return periods have been provided. These values can be used to forecast the potential height of storms up to periods of time 10 times the record length (e.g. from a 5 year long wave record the significant wave height of a 1 in 50 year storm could be predicted).

The grouping of storm events should also be taken into consideration as storm events occurring within a few day of each other are more likely to yield more extensive sediment redistribution than a single event alone (Callaghan et al., 2008). This was performed by visually examining the grouping of storms in time identified through the peaks-over-threshold method.

### 2.2.5 Sediment mobility

#### 2.2.5.1 Sediment threshold for transport

In order to determine whether or not tidal, wave and combined conditions are sufficient for sediment transport to occur the roughness length, $z_0$, of the bed can be calculated using the following equation:

$$z_0 = \frac{k_s}{30} = \frac{2.5d_{50}}{30} \quad (2.7)$$
where $k_s$ is the turbulent kinetic energy of the sediment.

For cohesionless sediments the dimensionless grain size, $D_*$, is determined using Equation 2.8

$$D_* = d_{50} \left( \frac{(s - 1)g}{v^2} \right)^{\frac{1}{3}}$$

(2.8)

where $s = \rho_s/\rho$, in which $\rho_s$ is the density of the grain mineral (kg m$^{-3}$, usually estimated to be 2650kg m$^{-3}$ for quartz/silicate sediments) and $\rho$ is the fluid density (kg m$^{-2}$), usually assumed to be 1027kg m$^{-2}$ (but can be calculated where salinity and temperature are known), and $v$ is the kinematic viscosity of the fluid (m$^2$s$^{-1}$).

From this the threshold for motion, $\theta_{2.5,cr}$ (where the subscript 2.5 denotes that $k_s$ was found using Equation 2.7), can then be estimated using Equation 2.9, where Equation 2.9a is used when $D_*$ is less than 10 (fine sand) and Equation 2.9b is used when $D_*$ is greater than 10.

$$\theta_{2.5,cr} = \frac{0.24}{D_*} + 0.55[1 - \exp(-0.02D_*)]$$

(2.9a)

$$\theta_{2.5,cr} = \frac{0.3}{1 + 1.2D_*} + 0.55[1 - \exp(-0.02D_*)]$$

(2.9b)

Finally the critical shear stress (Nm$^{-2}$) is found using Equation 2.10

$$\tau_{cr} = \theta_{cr} \cdot g(\rho_s - \rho)d_{50}$$

(2.10)

in which $g$ is gravity, taken to be 9.81ms$^{-1}$.

### 2.2.5.2 Current skin-friction shear-stress

Using Equation 2.11a where $0 \leq z \leq 0.5h$ and Equation 2.11b where $0.5h \leq z \leq h$, the depth-averaged tidal velocity can be estimated from the surface velocity $U(0)$ approximated from tidal diamond data

$$\bar{U} = \frac{U(z)}{(z/0.32h)^{\frac{1}{2}}}$$

(2.11a)

$$\bar{U} = \frac{U(z)}{1.07}$$

(2.11b)
The current related bed shear stress, \( \tau_c \) (Nm\(^{-2}\)) can be calculated from the expression

\[
\tau_c = \rho C_D (\bar{U}^2)
\]  

(2.12)

\( \bar{U}^2 \) is the depth-averaged current speed (ms\(^{-1}\)) and \( C_D \) is the dimensionless drag coefficient determined using Equation 2.13

\[
C_D = \left[ \frac{0.40}{\ln(h/z_0) - 1} \right]^2
\]  

(2.13)

where \( h \) is the mean water depth (m) and \( z_0 \) is the hydraulic roughness length found using Equation 2.7.

The value of \( \tau_c \) is then non-dimensionalised using Equation 2.14

\[
\theta_{2.5} = \frac{\tau}{(\rho_s - \rho)gd_{50}}
\]  

(2.14)

The value for Equation 2.14 can then be compared to the threshold of transport from Equation 2.9. If \( \theta_{2.5} > \theta_{2.5,cr} \) then the tidal velocities are sufficient for bedload transport to occur, i.e. there are live-bed conditions. If \( \theta_{2.5} < \theta_{2.5,cr} \) then the tidal velocities alone are insufficient for bedload transport to occur and instead clear-water conditions are observed. In situations where the shear stress is close to the threshold for transport grains smaller than the \( d_{50} \) are likely to be mobile.

### 2.2.5.3 Wave friction shear stress

To a first degree approximation, oscillatory flow is felt at the seabed when Equation 2.15 is satisfied:

\[
h < 10H_s
\]  

(2.15)

where \( h \) is the water depth and \( H_s \) is the significant waveheight. In certain locations, e.g. deep-water wreck sites and/or sites with low wave exposure, this equation may be sufficient to rule out wave-driven currents as being a dominant process at the site. Where sites do not meet this criteria then the wave related bed shear stress should be calculated using the following methodology.

The standard deviation of the bottom orbital velocity (\( U_{rms} \)) beneath a JONSWAP spectrum of waves is found using \( T_n/T_z \), where \( T_n \) equals \( h^{1/2} \) and \( T_z \) is the zero crossing period. This can be performed for wave-buoy data using the ubspecpar m-file supplied
by Wiberg and Sherwood (2008). Using this value and following the steps outlined by Soulsby (1997, p.79) the wave related bed shear stress, $\tau_w$, is calculated.

Firstly, the bottom orbital velocity amplitude $U_w$ is found using Equation 2.16.

$$U_w = \sqrt{2U_{rms}}$$  \hspace{1cm} (2.16)

From this the semi-orbital excursion ($A$) is derived using Equation 2.17.

$$A = \frac{U_w T_p}{2\pi}$$  \hspace{1cm} (2.17)

Using $A$ the rough bed friction factor ($f_{wr}$) is determined using Equation 2.18.

$$f_{wr} = 1.39 \left( \frac{A}{z_0} \right)^{-0.52}$$  \hspace{1cm} (2.18)

The smooth bed friction factor, $f_{ws}$, is then found through calculating the wave Reynolds number, $R_w$ using Equation 2.19, which is then fed into Equation 2.20.

$$R_w = \frac{U_w A}{v}$$  \hspace{1cm} (2.19)

$$f_{ws} = BR_w^{-N}$$  \hspace{1cm} (2.20)

For Equation 2.20 if $R_w \leq 5 \times 10^5$ then $B=2$ and $N=0.5$ (laminar), if $R_w > 5 \times 10^5$ then $B=0.0521$ and $N=0.187$ (smooth turbulent).

Finally, the wave related bed shear stress is calculated using Equation 2.21.

$$\tau_w = 0.5\rho f_w U_w^2$$  \hspace{1cm} (2.21)

For periods of time where $\tau_w > \tau_{cr}$, we would predict or observe mobile sediment. The inverse is also true. From this condition the percentage of time that the seabed is mobile through wave driven flow can be estimated.

### 2.2.6 Wave-current interaction

The bed shear stress due to the combined wave-current motion is calculated using the mean shear stress $\tau_c$ from combined wave and tidal flow using Equation 2.22.
\[ \tau_m = \tau_c [1 + 1.2 \left( \frac{\tau_w}{\tau_c + \tau_W} \right)^{0.32}] \]  

(2.22)

Maximum shear stress \( \tau_{max} \) from combined wave and tidal flow is calculated using Equation 2.23,

\[ \tau_{max} = \left[ (\tau_m + \tau_W \cos \phi)^2 + (\tau_W \sin \phi)^2 \right]^{0.5} \]  

(2.23)

where \( \phi \) is the angle between the wave and current shear (°). As with currents and waves alone, when this value of shear stress exceeds the critical threshold for transport then we would expect to observe a mobile seabed.

2.2.7 Storm history

Often wave buoy records are limited to the past 10 or so years, largely because the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) WaveNet program didn’t become operational until 2002. Because of this, wave data must be supplemented with historical accounts and storm surge records derived from tide gauges (which extend back to 1915 in some locations). By doing so the storminess of the MBES observational period can be put into context of the past century. Whilst these two time-series can capture the same storm events (Brooks et al., 2016), what each record captures is subtly different. Wave buoy records describe the dynamics associated with storm events and thus can be used to describe the potential bed dynamics. Whereas, tide gauge observations provide more of a idea of the periodicity of storm events through time. Because of these differences caution should be applied when using these two series in tandem.

Table 2.13: Sources of storm data, their location, dates, coverage and comments on their disadvantages and advantages.

<table>
<thead>
<tr>
<th>Source</th>
<th>Dates</th>
<th>Formats</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>BODC UK Tide Gauge Network</td>
<td>1915 onwards</td>
<td>Sea level (m) every 15-30 minutes</td>
<td>43 sites UK wide (Figure 2.9)</td>
</tr>
<tr>
<td>‘Historic storms of the North Sea, British Isles and Northwest Europe’ Hubert and Frydendahl (2005)</td>
<td>Last 500 years</td>
<td>Largely descriptive, with some synoptic charts and recordings of pressure change and wind strength</td>
<td>Descriptive rather than quantitative</td>
</tr>
</tbody>
</table>
2.2.7.1 Processing tide gauge elevation data

The storminess of the site can be observed through analysis of the non-tidal residual from tide gauge elevation time-series following the methodology of Wadey et al. (2014) using data from the BODC (Table 2.13), processed using MATLAB®. The average tide gauge record is 36 years long; therefore, often this record extends back past wave buoy data which is often restricted to the past 10 years. This time-series gives an estimate of the storminess of the MBES survey period in comparison to other periods of time. The methodology of Wadey et al. (2014) captures events where water levels were above the predicted astronomical tide, termed storm surges. This record acts as a good proxy for coastal storm events (Brooks et al., 2016). From this the return period of each storm event can be calculated using the national extreme value statistics provided by Mcmillan et al. (2011). If it appears that the MBES observational period has been quiet in terms of storminess then potentially the time-series may be insufficient to capture the effects of a significant storm event.

Furthermore, if a time-series of elevation is sufficiently long (>29 days) then the constituent parts from which the tide is constructed (e.g. principle lunar semi-diurnal (M2) and principle solar (S2) can be derived (Iyer and Couch, 2009; Pawlowicz et al., 2002). From these the tide can be reconstructed for any point in time. From this the tidal state during survey and during the wrecking event can be calculated.
2.2.8 Bedform analysis

The combined tidal and wave forcing can result in the transport of sediment across a wreck site. Often this occurs through bedload transport in the form of bedforms. Through tracking the migration of bedforms within the MBES data the net transport direction and strength can be quantified. Often this provides higher spatial resolution of hydrodynamic processes at the site then wave and tidal data permits.

2.2.8.1 Crest-crest/trough-trough migration

Where bedforms are visible in MBES data the position of bedform crests/troughs can potentially be tracked over some period of time (the survey interval), so long as the bedforms can be positively identified between the two surveys (i.e. they have a distinctive morphology). By dividing the distance migrated by the time interval between the surveys the rate of migration can be calculated. Whilst crest-crest migration has been used more commonly in the literature (e.g. Hanes, 2012; Knaapen, 2005), Ernstsen et al. (2006b) recommended using the trough to rough migration, since the crest position displayed more variability over a single tidal cycle.

2.2.9 Historical chart analysis

An understanding of the multi-decadal stability of the regional area (scale of 100’s metres) is useful when determining the effects of the hydrodynamic environment on the sediment transport regime at shorter time scales (multi-annual). By digitising historical charts using ArcMap the change in the location of depth contours with time can be mapped, describing both the spatial evolution and potential accretion/erosion of seabed features such as sandbanks and channels.

Historical charts can be accessed from the United Kingdom Hydrographic Office (UKHO) archives and date back to, at the very latest, the beginning of the 20th C. When comparing charts careful attention is paid to the units of depth as well as the datum used as this changes from chart to chart.

Since more recent charts have a higher positioning accuracy, charts should be georectified in reverse chronological order. Charts made prior to the 1950’s would have relied on using sextant angles for positioning, with an error of approximately ±3 - 5m (P. Woodgate, pers. comm., 28 Nov. 2013) and lead lines for depth measurements. Burningham and French (2011), who also used georeferenced historical charts of the Thames area, estimated the vertical error to be ±1m. On top of these surveying errors there is also an error associated with the plotting precision, which is usually taken to be 0.3mm (The United Kingdom Hydrographic Office, 2009). So, for example, a chart scale of 1:12,160 would give a ground precision value of 36m.
Once the more modern charts are georeferenced then older charts can be aligned to these. Charts are preferentially georectified using coordinate graticules. Where these were not within the limits of the scanned area positions of buoys and other fixed features can be used. In order to judge the accuracy of the transformation georeferencing-associated RMS values, provided within the ArcMap georeferencing tool, can be consulted.

From these georectified charts features of interest, such as banks and channels, can be hand-contoured. The geometric centre (centroid) of these features can then be calculated within ArcMap. From this the position of the feature and thus its movement over time can be quantified.

### 2.3 Archaeological Data

It is all too easy to forget that the multibeam target on the seafloor represents not just a hull of a vessel but a rich archaeological deposit that has survived some period of time. In addition, the site may have been investigated and documented by archaeologists over several years or even decades. These irreplaceable resources signify enormous investments of money, skill and time and often capture the cutting edge of engineering from the period in which they were constructed (Adams, 2001, p.301). An understanding of the taphonomic processes occurring at these sites is invaluable information for maritime archaeologists attempting to understand the formation of these sites and potentially preserve them for future investigation and even excavation.

It is vital to have an appreciation of the archaeological background of these sites to inform the taphonomic analysis of the site. For example, if protective matting has been put in place to aid the burial of a wreck this is key information when interpreting MBES time-series. Also, archaeological sources have details on the wrecking process, e.g. was it abrupt or did it occur over a period of days; from the later we would expect a more dispersed deposit, which otherwise might be interpreted as being the result of the hydrodynamic conditions at the site. An idea of the construction materials and the cargo of the wreck can assist in the identification of certain features in the MBES data and when these can be related to a position within the vessel can be used to give an idea of the integrity of the spatial relationships between artefacts and superstructure.

#### 2.3.1 Useful information

**Dimensions**

This will impact upon the extent (both depth and spatial) of the scour-accumulation surrounding the wreck. This information can also be used to determine how much of the wreckage/if any has been lost and finally can be used to determine the orientation of the wreck (e.g. whether it is lying on its side or keel).
Chapter 2 Data collection and methods

Construction material
The construction material will impact upon the rate at which the vessel breaks up and the containment of artefacts. Wooden vessels are more likely to undergo biological wear, whereas metal wrecks are more likely to be exposed to chemical erosion.

Vessel construction date
Similarly to construction material, the vessel construction date gives an idea of the types of materials and methods used in the wreck’s construction. Also, the length of the vessels operational life (the sinking date minus the construction date) is useful in determining whether or not the vessel might have undergone major alterations since it was laid down and gives the window of time for which the artefacts on-board the wreck may describe.

Vessel sinking date
The length of the period over which the vessel has remained on the seafloor will alter the present day observed conditions at the site. More modern wreck sites might not yet have reached equilibrium with their surrounds (Section 1.2.4) and so may represent more open systems potentially loosing material.

Site maps
Where the resolution of MBES is insufficient to resolve individual artefacts site maps can be used to determine the spread of artefacts at the site and potentially any net transportation pathways. Used in conjunction with MBES surfaces site maps can potentially be used as a time-step in a similar manor to historic charts.

Cargo type
Knowledge of the cargo type can be used to estimate the transportation potential of artefacts, e.g. small coins are likely to be transported at lower velocities or buried than a cannon. The constituent material of the artefacts can also be used to infer the site conditions, e.g. if fragile textiles and organics are present on the surface the site then it is likely that recent erosion has occurred at the site, since these objects are not usually preserved unless they remain buried.

Description of wrecking event
The duration and the tumultuousness of the wrecking event will impact upon the damage done to the wreck superstructure and the distribution of the artefacts. If a wreck is floundering at the surface for a long period of time then it is more likely that the crew will have had time to lighten the load (removal of cannons and other heavy objects). If a description of such a wrecking event was not available then it would be easy to misinterpret the large spatial distribution of artefacts as being a result of the seafloor conditions, rather than as a result of the wrecking event itself.

Management of the site
Knowledge of whether or not there have been any anthropogenic disturbances at the site (e.g. excavation, protective measures such as mats and sandbags) is of importance when
interpreting the MBES time-series of the site. These disturbances could force the site to a new equilibrium or towards disequilibrium (Section 1.2.4). Also, whether or not the site is protected will impact upon the types of activities occurring at the site which could potentially alter the archaeological deposit, e.g. recreational diving.

2.3.2 Sources

Conflicting evidence is often found from individual reports, therefore a range of historical/archaeological accounts must be consulted, and when there is a conflict of accounts the reliability of the source must be determined. A range of library and online collections were used to source relevant data. From these locations three key sources for information were identified:

- The UKHO wrecks database (SeaZone). This database provides basic information on each wreck (such as date of sinking, location, depth of site, measurements of the wreck) as well as a time-line the management of the site.
- The Lloyd’s Ship Register. Perhaps the most comprehensive record of wreck and ship information. Not yet available digitally in its entirety, but increasingly more records are freely available online (Lloyd’s Register, 2015).
- Shipwreck index of the British Isles (Larn and Larn, 1995). Although a secondary source of information (often extracted from Lloyd’s register) this book gives a short account of the vessel’s statistics and an account of the wrecking event

2.4 Summary

Through following the methods developed within this chapter a vigorous collection of data is assembled that describes both the taphonomy of the wreck site as well as the environmental and archaeological conditions that may have controlled and altered the taphonomic pathway. To this end, two key components in creating a robust description of the wreck site and its environment are established:

i. Through the assessment given in this chapter of the available MBES, environmental and archaeological data it is clear that rarely can a singular source be used to provide sufficient data. Often higher resolution time-series are restricted to the past 5 to 10 years (e.g. in the case of most wave buoys). Instead a collection of multiple sources of data must be used to allow for the creation of an extended (both the temporally and spatially) understanding of the wreck site. For example, to extend the storm record back in time the wave buoy record is supplemented with data from tide gauges to extend the record back by several decades.
ii. Furthermore, the quality of these data ranges widely. For example, MBES data are often given with an uncertainty in the region of 10's of centimetres (International Hydrographic Organisation (IHO), 2008). As a result, an assessment must be made as to the robustness in order to gain some understanding of the potential uncertainties involved. Only then can the ‘real’ properties of the site be determined.

Additionally, throughout this chapter methods of best practice in order to reduce and better constrain data uncertainty have been identified. These are summarised in Table 2.14.

In the following two chapters, the methods developed in this chapter will be employed at five different wreck sites. Whilst the first key component above can be adequately addressed, as it will be discovered by the end of Chapter 4, a further review of the methods used to assess the uncertainty of the MBES data is required. To this end, Chapter 5 proposes a new methodology to be utilised when using MBES time-series in future assessments of change.
Table 2.14: Summary of recommended best practice.

<table>
<thead>
<tr>
<th>Source</th>
<th>Recommended best practice</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MBES</strong></td>
<td></td>
</tr>
<tr>
<td>Collation and formats</td>
<td>Collate unprocessed bathymetric data when feasible</td>
</tr>
<tr>
<td>Sonar measurement uncertainty</td>
<td>Estimate the quality of the acoustic signal</td>
</tr>
<tr>
<td>Attitude offsets, accuracy and</td>
<td>Carry out rigorous patch testing and ensure that these data are kept with the MBES data</td>
</tr>
<tr>
<td>precision</td>
<td>files. Collect real-time attitude sensor uncertainties</td>
</tr>
<tr>
<td>Position</td>
<td>Use <strong>RTK GPS</strong></td>
</tr>
<tr>
<td>Vessel configuration</td>
<td>Use a total station to measure offsets and determine standard deviation of calculations</td>
</tr>
<tr>
<td>Sound velocity measurements</td>
<td>Perform a <strong>SVP</strong> at the very minimum at the start and end of the survey (time interval</td>
</tr>
<tr>
<td></td>
<td>between <strong>SVPs</strong> is dependent on the variability of the water column sound velocity)</td>
</tr>
<tr>
<td>Datums</td>
<td>Ensuring surveys are converted to the same datum using the same method of conversion negates</td>
</tr>
<tr>
<td>Tidal correction</td>
<td>the requirement of subtracting the tidal elevation from the depth since soundings are</td>
</tr>
<tr>
<td></td>
<td>referenced to a true vertical datum</td>
</tr>
<tr>
<td>Sea state</td>
<td>Surveys should be carried out during calm sea states. Real-time attribute uncertainty</td>
</tr>
<tr>
<td></td>
<td>should be collected so that the impact of the sea state on the data quality can be</td>
</tr>
<tr>
<td></td>
<td>constrained</td>
</tr>
<tr>
<td>Gridding data</td>
<td>Ensure all surveys are gridded to the same grid. This should not be at a resolution finer</td>
</tr>
<tr>
<td></td>
<td>than the coarsest survey resolution</td>
</tr>
<tr>
<td>Interpolation method</td>
<td>Ensure interpolation method is suited to data (i.e. is fit for the resolution, bathymetric</td>
</tr>
<tr>
<td></td>
<td>complexity etc.) and that the same methodology is used for each survey</td>
</tr>
<tr>
<td><strong>Environmental Data</strong></td>
<td>Often a single dataset is not sufficient and a series of sources must be used in tangent</td>
</tr>
<tr>
<td></td>
<td>to quantify the site specific environmental conditions.</td>
</tr>
<tr>
<td><strong>Archaeological Data</strong></td>
<td>A range of historical/archaeological accounts must be consulted, and when there is a</td>
</tr>
<tr>
<td></td>
<td>conflict of accounts the reliability of the source must be determined</td>
</tr>
</tbody>
</table>
Chapter 3

The SS Richard Montgomery

3.1 Introduction

On August 20th 1944 the SS Richard Montgomery (National Monuments Record 904735 and United Kingdom Hydrographic Office (UKHO) wreck number 12800) grounded on Sheerness Middle Sand bank, 2km off the Isle of Sheppey, in the Outer Thames Estuary (Figure 3.1). Due to the wreck’s potentially explosive cargo of ammunition she was deemed hazardous, left in situ and was the first wreck to be protected under section 2 of the 1973 Protection of Wrecks Act. The wreck has since been a continual topic of contention. Recent proposals for an airport within the Thames Estuary and the construction of the London Gateway port just 10km to the north (Figure 3.1), have reignited the debate over the wreck, with the site receiving mention both in the news (BBC News, 2004, 2005a,b, 2011; Brown, 2011; Horsnell, 2004; Johnson, 2004; Kirby, 2004; Leafe, 2012; Sherlock, 2013; Telegraph, 2011, 2013) and a popular science article (Hamer, 2004).

Multibeam bathymetry surveys of the site have been carried out for the past 17 years, providing 14 high resolution (horizontal resolution <0.5m) bathymetry surfaces of the wreck and surrounding area, as well as numerous diver surveys, making it, to the author’s knowledge, the most repeatedly surveyed marine archaeological site.

Accounts of the wrecking event have been published by several authors (Atkinson et al., 1972; Elphick, 2001; Turner, 2005). These reports have gone a considerable way to bringing together much of the historical literature surrounding the wreck, however, this chapter (originally published as Astley et al., 2014) is the first publicly available academic literature to bring together these sources of information and goes further by enhancing the record through the inclusion of modern oceanographic data.

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This chapter is based on work published as Astley et al. (2014) (Section 3.3.3.1 up to 3.4.1) and is awaiting publication as Astley et al. (in review, a) (all other sections).
Whilst the data-series for the *Richard Montgomery* site is exceptional and unlikely to be matched by any other archaeological wreck site, the knowledge gleaned from this work has wider implications for the management of submerged wreck sites. In order to ascertain these implications this chapter has three main aims: first, to give a full account of the wrecking process; second, to describe the archaeological taphonomy of the wreck through a discussion of the local geology and hydrodynamics of the site; finally, to review the past, present and future management of the site.

![Figure 3.1: Location of the wreck of the SS Richard Montgomery, London Gateway Port, proposed site for the Thames Hub Airport and the locations of the Maplin Sands Acoustic Wave and Current (AWAC) buoy and Herne Bay tide and wave step gauge sites.](image)

### 3.2 History and archaeology of the ship

#### 3.2.1 Construction of the ship

Built in Florida in July 1943, the SS *Richard Montgomery* (Figure 3.2) was one of 2,710 emergency wartime cargo Liberty Ships, with the purpose of carrying ammunitions (*Records of the Admiralty Naval Forces Royal Marines Coastguard and related bodies, 1974*). Named after General Richard Montgomery, an Irish-American soldier who was killed during the American Revolutionary War, she was the seventh out of 82 American Liberty Ships built by the St. Johns River Shipbuilding Company (*Sawyer and Mitchell, 1985*).
The cost of each Liberty Ship varied between yard in spite of the same build specifications. This led to the Richard Montgomery, built at St Johns River Shipbuilding Company, costing $2,100,000 (£1,230,000) (Elphick, 2001), which equates to almost $30,000,000 (£17,000,000) in 2014. This was $600,000 (in 1940’s currency) more than the rival Wilmington shipyard.

The Richard Montgomery was a type EC2-S-C1 vessel, an emergency cargo ‘EC’ ship, of size ‘2’ (between 120 and 140m in length), powered by a triple expansion, three cylinder, steam engine ‘S’ and of design ‘C1’. The hull of the Richard Montgomery was 422.8ft (128.9m) long, with a maximum beam of 57ft (17.4m) and a depth of 34.8ft (10.6m) (Lloyd’s Register of Shipping, 1944b). The ship would have been capable of reaching speeds of 11 knots (Davies, 2004; Sawyer and Mitchell, 1985). EC2-S-C1 ships were built with five holds (Figure 3.3), three forward of the engine and boiler and two aft.

Rules of war stated that all armament on merchant ships should be confined abaft the beam (Thomas and Duncan, 1999), but since German forces had previously flouted this rule Liberty Ships were equipped with weapons which could be fired ahead. Liberty Ships were built with accommodation space for up to 81 crew and gunners (Sawyer and Mitchell, 1985). However, on her final voyage, the Richard Montgomery carried a crew of just 42, together with 25 Naval Armed Guard to man the guns (Elphick, 2001).

Despite the Liberties’ armament, during the war 273 of the 2,710 Liberty Ships sank (a rate of 10%) (Sawyer and Mitchell, 1985). Most accounts agree that the Montgomery’s sinking was due to grounding on the Sheerness Middle Sand bank (Atkinson et al., 1972; Elphick, 2001; Hamer, 2004; Johnson, 1982; Records of the Admiralty Naval Forces Royal Marines Coastguard and related bodies, 1974). However, inconsistencies in the story of the wrecking process exist and are discussed later in Section 3.2.3.
Following the war and post-war clear up operations, the remaining Liberty Ships were often refitted for a different use or were scrapped for their metal content. Approximately one third, 900, of the Liberties were traded commercially after the war (Elphick, 2001). Just two operational Liberty Ships remain, the SS *John W. Brown* and the SS *Jeremiah O’Brien* (Sawyer and Mitchell, 1985) (both berthed in the United States). Therefore, the *Richard Montgomery* is historically and archaeologically significant as it represents a Liberty Ship in its original form.

![Inboard profile and plan-view layout of the SS Richard Montgomery.](image)

Figure 3.3: Inboard profile and plan-view layout of the SS *Richard Montgomery*. Adapted from Atkinson *et al.* (1972)

### 3.2.2 Wrecking event and emergency salvage

In the first twelve months following her launch, the *Richard Montgomery* made three round trips between US ports and Britain, and one to the Mediterranean. On the whole these trips were uneventful, with the *Richard Montgomery* only coming under attack from German aircraft once (Elphick, 2001).

On her final deployment, the vessel sailed to Hog Island, Philadelphia, on the Delaware River, where she was loaded with 13,064 general-purpose 250 lb. bombs, 9,022 cases of fragmentation bombs, 7,739 semi-armour-piercing bombs and 1,522 cases of fuses (Atkinson *et al.*, 1972), equating to approximately 6,000 tonnes (see Table 3.1 for range of estimated cargo weights). The vessel was also ballasted with 950 tonnes of coal slag (Elphick, 2001).

The *Richard Montgomery* departed from New York City on the 25th July 1944 as part of a 137 strong convoy, HX-301 (Records of the Admiralty Naval Forces Royal Marines Coastguard and related bodies, 1974). Intended for Cherbourg, France, she arrived in the Thames Estuary on the 16th August and was ordered to wait in the mouth of the
Thames for the formation of a convoy before sailing to Cherbourg. Once she entered the waters off Southend she was under the Thames Naval Authority, directed from HMS *Leigh* (Southend Pier) (*Records of the Admiralty Naval Forces Royal Marines Coastguard and related bodies, 1974*).

![Diagram](image)

**Figure 3.4:** Areas surrounding the Great Nore Anchorage site (spatial limits shown for 1924 - 1930 (green) and 1966 (orange; no limits provided in 1940’s charts), where, for the SS *Richard Montgomery*, water depths at low water spring tide (0.6m above Chart Datum; CD) would have provided water under the keel (in blue) and possible stranding locations, areas where the water depth was shallower than the draft (cream). Bathymetry is from a 2008 survey and so there will be some discrepancies due to sea-bed erosion/accumulation and dredging activities.

The estuary was busy and so she set anchor in the Great Nore anchorage off Sheerness, with a depth range of 8 - 16m below Chart Datum (CD) and which was used as an examination anchorage for merchant vessels (marked on admiralty charts pre-1937; *The London Gazette, 1918*) (Figure 3.4). The average draft of a EC2-S-C1 type Liberty Ship, of 8.5m (*Sawyer and Mitchell, 1985*), would have allowed for 1.5m of water under the vessel at low tide. The *Richard Montgomery*, however, was trimmed to a draft of 9.4m, giving a clearance of just 0.6m at low tide (*Atkinson et al., 1972*). The area is bounded by Sheerness Middle Sand to the south and Nore sand to the northwest, creating an area just 650m wide with waters deeper than the draft of the *Montgomery*. Figure 3.4 (cream-coloured area) shows the area in which the *Montgomery* would have had to have drifted in order to strand at spring water low tide (0.6m above CD). Startlingly, some of this area is even contained within the anchorage bounds.
On the night of the 20th August 1944 the winds shifted northerly, coinciding with the peak spring tide of 5.54m (Figure 3.5), and the Montgomery swung towards the shoal. Vessels in the vicinity of the Richard Montgomery saw that she was heading perilously close to the bank and began to sound their sirens in warning (Elphick, 2001). The Master lay asleep in his cabin and his Chief Officer, who had been on anchor watch at the time, did not wake him. As the tide ebbed her plates strained and buckled, making a noise which could be heard up to a mile away (Elphick, 2001). Taking the depth of stranding of the vessel to be 6m CD, the wreck would have become grounded when the tide ebbed to a depth of 3.4m, which would have occurred at 2:30am on the morning on the 20th August (Figure 3.5).

Having stranded on Sheerness Middle Sand on a spring tide the only way to free her would be to remove some of the ammunition and to await the next spring tide on the 5th September (Figure 3.5). Five volunteers and two signalmen remained on board the vessel whilst the rest of the crew were evacuated using the life-vessels (Elphick, 2001).

The task of removing the munitions was handed to Master Stevedore T. P. Adams of Watson and Gill, Shipbrokers of Rochester, who arrived at the site at 3am on Tuesday 22nd August (Atkinson et al., 1972). On Wednesday 23rd August 1944 the operation began. However, by 3pm the next day her hull cracked open transversely at the forward end of hold number three, which flooded through to holds number one and two. In spite of her rapidly worsening condition a non-stop six hour Board of Enquiry was held on board in the ship’s saloon. The Board found that the Master hazarded his ship. Consequently, the Master and the Chief office were suspended for 12 months.
The *Richard Montgomery* finally broke her back on the 8th September. Salvage continued until the 25th September, when shortening daylight hours and worsening weather prevented any further headway, successfully clearing holds four and five (Treasury Solicitor and HM Procurator General, 1952). Approximately half of her cargo was recovered, leaving an estimated 3,000 tonnes still in her fore part (See Table 3.1 for estimates) (Treasury Solicitor and HM Procurator General, 1952).

Official accounts of the wrecking paint a fairly unceremonious event. For example, the wrecking event was recorded in the Lloyd’s register of shipping, with the circumstances listed as ‘On Nore Sands’ (Lloyd’s Register of Shipping, 1944a) (this account is also incorrect, since the Nore Sands are to the northwest of the wrecking site; this and other inaccuracies are discussed in the following section). Were the event to have occurred outside of war-time perhaps the incident would have been seen as more noteworthy.

Removing the stern cargo increased the ship’s buoyancy allowing it to pivot at the deck level. After flooding this section of the vessel separated and moved approximately 15m south (Figure 3.6ai) and pivoted clockwise before settling on the seabed (Figure 3.6bi). A sonar survey in 1952 revealed the fore-section settled oriented 358° (True) and the aft section 11° (True).

By 1965 the forward hull had listed 11° towards starboard, and the aft hull 15° towards starboard (United Kingdom Hydrographic Office (UKHO), 1965), though these may have been the initial settling positions of the sections, since no measurements were made immediately post wrecking. The forward and aft sections had also pitched 4° and 2° away from the break towards the bow and stern, respectively. Sediment had built up along the mid part of the forward section to almost deck level and to the level of the bottom of the holds along the aft section. Scour had dropped the sediment level at the tip of the bow and stern, revealing the propeller and rudder, and in the gap between the two hull sections.

By 1972 it was reported that the forward section was orientated 357° True and the aft section 15° True (an increase of 4° since 1952). Diver surveys in 1972 also observed the list of the forward hull section had increased to 16° towards starboard (an increase of 5°) and the list of the aft section had remained within error at 14°. A minimum gap between the two sections of 9.1m was recorded. The 1972 diver survey showed no other change in the structure of the vessel and the pitch of the two hull sections remained constant. However, a difference in ‘mudlines’ was observed (Figure 3.6ai). The previous mound of accumulation along holds 2 and 3 observed in 1952 appears to have flattened out by 1972. Conversely, the previously flat section along hold 4 and 5 grew by approximately 5m between 1952 and 1972.

Modern bathymetry data (1995 - 2012) indicate that the orientation of the forward section has not significantly changed since the 1972 diver survey (Figure 3.6bii). The orientation of the aft section is now closer to 11° (True), the same as the orientation noted in
Figure 3.6: a) Port-side of the wreck from i) 1965 diver survey performed by Mr J Alexander (CSO South Coast) with 'mud-lines' from the 1965, 1972 and 2012 surveys, ii) point cloud and seabed bathymetry from the 2012 bathymetry survey. b) Vertical view of the wreck from i) 1965 diver survey and ii) 2012 point cloud.
1952. Therefore, it seems likely that the value of 15°, given in 1972, was inaccurate. The gap between the two sections remained within 10cm of the value reported in 1972 (Figure 3.6bii) (a minimum of 9.1m). The forward section list has increased to 17° in 2006 (1° since 1972). However, the aft section list remained unchanged. The pitch of the forward section increased from 4° towards the bow in 1952 to 9° towards the bow in 2006, whereas the aft pitch of the aft section increased by just 1° to an angle of 3°.

In summary, the forward section has been more mobile in terms of its rotation in comparison to the aft section, which has maintained almost the exact same pitch and roll since 1952. This is likely due to one of two factors or a combination of both: i) the initial orientation of the sections; the forward section is less perpendicular (aligned 97° to the oncoming flow) than the aft section (aligned 88° from the flood flow). Therefore, the upstream scouring has created a consistently deep channel alongside the forward section, whereas the scouring along the aft section is confined to the propeller area only, and/or ii) the forward section remains fully laden and the moment pulling this section over is greater than the emptied aft section.

Since 1965 a crack on the port side, along the number 2 tween deck, has been observed and monitored. Liberty Ships took an average of 50 days to build and were designed to have a useable life of just five years (Thompson, 2001). The rapid ‘conveyor-belt’ production of Liberty Ships often led to numerous structural issues. The grade of steel used often suffered embrittlement when exposed to the cold waters of the North Atlantic (Sawyer and Mitchell, 1985, p. 11). This issue was made worse by the use of welded (as opposed to riveted) hull construction, which allowed cracks to run further distances across the hull (Elphick, 2001). Over 1,200 Liberty Ships suffered brittle fractures (Marder and Fineberg, 1996) and three out of the 2,710 Liberty Ships constructed broke in half whilst underway (Sawyer and Mitchell, 1985). It is likely that this weakness contributed towards the rapid break-up of the Richard Montgomery’s hull and possibly the split in the number 2 tween deck.

### 3.2.3 Inaccuracies in the record

At least four accounts of the Richard Montgomery’s demise report that the Richard Montgomery was attacked by German aircraft in the Thames Estuary approaches and that the vessel was subsequently towed in and anchored (Davies, 2004; English Heritage, 2012; Moore, 1993; Sawyer and Mitchell, 1985). No surveys of the vessel have reported any damage to the ship which would suggest it had been attacked and so it is likely that these findings are false and relate to an encounter with German aircraft on a previous operation as reported by Elphick (2001). Moore (1993) collated his literature material from the Merchant Vessels of the United States (MVUS) record and exclusively states the ship was bombed on the 20th August while anchored in the Thames, the ship was then towed and run aground on Nore Sands (another inaccuracy, as the Nore Sands is north-west of
the wrecking site). Whilst Sawyer and Mitchell (1985) incorrectly stated that the Montgomery was bombed, the authors did, however, acknowledge that there are known to be different versions of the account of the Richard Montgomery’s demise. Davies (2004) gives Sawyer and Mitchell (1985) as his primary reference and so the irregularity is propagated through another account.

The remaining cargo is largely held within hold numbers 1, 2 and 3. However, estimates of the remaining number of devices and the weight this equates to vary from 2,625 tonnes to 3,846 tonnes, giving a Net Explosive Quantity (NEQ) (the weight without packaging, casing, bullets, etc.) between 1,088 and 1,500 tonnes (Table 3.1). The range of values likely results from the poor documentation of the removed cargo, which due to the rushed nature of the emergency salvage, is likely to be an underestimate of the total removed mass. Some of this confusion may also have stemmed from the misuse of tonne (1,000 kg) and ton (which can be either 907kg, if using US or short ton; or 1,016kg, if using Imperial or the long ton) and the use of both total weight and NEQ. Many accounts of the salvage report half the cargo having been removed (Blair and Richards, 2008; Defence Evaluation and Research Agency (DERA), 1997; Maritime and Coastguard Agency (MCA), 2000; Wille, 2005), and some reports have used this information to estimate the remaining cargo (UK Parliament, 1973). However, as they misquoted the initial cargo weight then they also over-estimated the remaining weight.

The most thorough, and so perhaps the most reliable source, is the 1997 Defence Evaluation and Research Agency (DERA) report. DERA, on behalf of the Maritime and Coastguard Agency (MCA), carried out a full literature review, considering both the sailing draft and salvage log, amongst other sources. A NEQ value of 1,400 tonnes was given. However, no total remaining weight was provided. This has been estimated by the author from a table of munitions weights and numbers given within the DERA report, from this a minimum value of 3,105 tonnes was found. This value does not include pyrotechnics or white phosphorous. Therefore, it is likely to be a slight underestimation, but due to the thoroughness of the study it is thought to be closest to a true value. Surprisingly this report gives by far the largest value for the initial weight of the cargo, at 9,000 tonnes, whereas the shipping draft, referenced within the DERA report gives a value of 6,225 tonnes. The implication of this is that no one source of information appears to be entirely infallible.

Conflicting accounts also exist about the state of the remaining wreckage. Atkinson et al. (1972) reported that in the early 1960’s a transverse break in the bow section between the forward mast and the forward end of the number 2 hatch occurred. Sawyer and Mitchell (1985) stated that by 1972 the wreck was in three parts and that this had been confirmed by the 1972 naval survey. The 1965 diver survey reported that the wreck remained in two sections but with buckled and split plating. Multibeam bathymetry surveys confirm there is a crack at hold 2 on the port side with dimensions 1.27m by 2.20m (Figure 3.7) and that the deck plating has collapse slightly inwards. However, this has
Table 3.1: Values of initial cargo weight and remaining cargo weight post-salvage in tonnes, from a range of literature. Lampe (1964) estimation is likely to be based on a message from General Dwight Eisenhower, dated 11 November 1944, UKX 13256, which gives a remaining tonnage of 3,691 US tons, equal to 3,348 tonnes.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Initial cargo</th>
<th>Remaining cargo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treasury Solicitor and HM Procurator General (1952)</td>
<td>6238</td>
<td></td>
</tr>
<tr>
<td>Lampe (1964)</td>
<td>5,443 -</td>
<td>3348</td>
</tr>
<tr>
<td>Lampe (1964)</td>
<td>6,350</td>
<td></td>
</tr>
<tr>
<td>United Kingdom Hydrographic Office (UKHO) (1965)</td>
<td>6669</td>
<td></td>
</tr>
<tr>
<td>Atkinson et al. (1972)</td>
<td>5558</td>
<td>2878</td>
</tr>
<tr>
<td>Hills (1978); Johnson (1982)</td>
<td>2625</td>
<td>1088</td>
</tr>
<tr>
<td>Larn and Larn (1995)</td>
<td>6225</td>
<td>2814</td>
</tr>
<tr>
<td>Maritime and Coastguard Agency (MCA) (2000)</td>
<td>6350</td>
<td>1270</td>
</tr>
<tr>
<td>Maritime and Coastguard Agency (MCA) (2003)</td>
<td>1361</td>
<td></td>
</tr>
<tr>
<td>Hamer (2004)</td>
<td>3000</td>
<td>1400</td>
</tr>
<tr>
<td>Johnson (2004)</td>
<td>7000</td>
<td>1400</td>
</tr>
<tr>
<td>Turner (2005)</td>
<td>5558</td>
<td>2878</td>
</tr>
<tr>
<td>European Maritime Safety Agency (2007)</td>
<td>6127</td>
<td>1500</td>
</tr>
<tr>
<td>United Kingdom Hydrographic Office (UKHO) (2010)</td>
<td>6225</td>
<td>3222</td>
</tr>
</tbody>
</table>

not gone as far as separating the forward section into two discrete sections. Additionally, there has been no change in the size of the crack from 2009 to 2012.

3.2.4 Responsibility and management of the wreck

The events following from wreckage of the SS Richard Montgomery up until present day, are described chronologically in this section and key events are shown on a time-line for clarity (Figure 3.8). This time-line highlights the eight year hiatus in activity which occurred directly after the wrecking. During the war the wreck was largely overlooked and was not formally addressed until 1952 when Dr R. Bennett, the Member for Gosport,
Figure 3.7: Crack and Hold 2 and collapse of deck plating from 2012 bathymetry survey. Data courtesy of MCA.

Figure 3.8: Timeline of wreck site management from sinking to present day.
raised the matter in the House of Commons (UK Parliament, 1952). The Admiralty responded to Dr Bennett’s questions, stating that the Admiralty had no responsibility for the wreck and that no measures were being taken to ensure it did not ‘blow up’. Instead the Admiralty stated that the responsibility for the wreck lay with the Port of London Authority (PLA). During wartime, agreements were made between the PLA and the Admiralty with regards to responsibilities of each authority during the war. This did not, however, affect the PLA’s responsibility for the removal of wrecks posing an obstruction to navigation. The PLA were unwilling to accept the liability for the expenditure involved in raising the wreck, claiming the wreck posed no risk to navigation.

Following the formal addressal in the House of Commons, a survey of the wreck was carried out that year by the PLA (Figure 3.9). This single-beam bathymetric survey provided the first glimpse of the deep scour pit that had been calved around the wreck just 8 years after the ship’s wrecking. Rapid scouring is often associated with the initial introduction of a structure to the marine environment. The majority of the observed scouring is likely to have occurred within the first few tidal cycles (Harris et al., 2010). Already this depression was greater than 7m deeper than the ambient seabed (58% of the maximum scour depth observed in 2012) and displayed a strong spatial asymmetry with the western lobes extending more than 150m downstream of the site, in comparison to the eastern lobes which extended just 50m away from the wreck.
Attempts were also made to hand the task of dealing with the wreck over to the United States naval forces who still maintained ownership of the Liberty Ships throughout the war. To complicate the situation further, in 1962 a letter sent from the commander in chief of the United States naval forces, stated that the vessel was raised in 1948 and sold to Phillips, Craft and Fisher Company the same year (Cohune, 1962). No attempts to raise and scrap the wreck were ever made and the Phillips, Craft and Fischer Company had sent a representative only to survey the wreck (Elphick, 2001).

Briefly setting aside the debate over whose responsibility the wreck was, in 1964 a working party made up of representatives of the Ministry of Defence (MoD), the PLA and the Medway Conservancy Board advised that the wreck should be left in situ and that a further diving survey should be conducted. A diving survey was conducted shortly thereafter in May 1965 by J Alexander (Figure 3.6ai). This survey confirmed the previously assumed deteriorating state of the wreck, but also established the relative stability of the position of the two hull sections.

The United States then, once again, became involved with the management of the wreck. In 1966, representatives of the United States carried out a re-appraisal of the explosive risk of the wreck. From this survey they recommended that the cargo should be salvaged, though this recommendation was not shared by British salvage experts and so the wreck was left in situ.

Finally in 1971 the Department of Trade and Industry, by de facto, accepted responsibility for the wreck. Following this a detailed survey of the wreck was carried out and physical modelling of the site was conducted by HR Wallingford in 1972, which aimed to determine the potential effectiveness of using blockships to protect the wreck from drifting large vessels. However, this report found that blockships would not be a feasible long-term solution for preventing collisions and instead proposed an elliptical protective barrier might be more suitable. Neither course of action was ever pursued further.

In 1973, with no outstanding plans for the removal of the wreck, it became the first wreck to be designated under the Protection of Wrecks Act 1973, Section 2, under which vessels that are deemed as being dangerous by virtue of their content are protected. A restricted area, with radius 200 yards (182m), was buoyed around the wreck and placed under 24-hour surveillance. This meant that, for the first time, there was a statutory power that could be invoked to keep unwanted people away from the wreck.

Until 1984, on a near decennial basis, surveys were carried out by the MoD using salvage divers. After which surveys were performed by commercial diving contractors, working under the MoD’s supervision. These were hindered by the poor visibility on the site and so ceased in 1993 (The Coastguard Agency, 1996).

From 1995 onwards, on an almost yearly basis, the wreck and the surrounding seabed have been surveyed using multibeam swath sonar. This work is carried out on behalf of
the MCA by contractors working under MoD supervision. Primarily these surveys have been conducted to assess the condition of the deteriorating hull and were used in combination with ultrasonic hull thickness analysis. The MCA were, and still are, interested in the stability of the surrounding seabed, primarily the triple-lobed scour pit which surrounds the wreck structure, as the wreck is provided some structural support from the underlying sediments. The loss of this support could result in the collapse of the hull structure and the dispersal or detonations of the presently contained munitions.

In 1999 the MCA commissioned BMT Reliability Consultants Ltd to carry out a study on the long term management of the wreck site (BMT Reliability Consultants Ltd, 2000). This study estimated the worst case financial cost of the detonation of the wreck to be in the region of £1 billion. Following on from this, on the 24th January 2005, the Department for Transport held a meeting to discuss the future management of the Richard Montgomery. Using the 2000 findings for guidance, a concise summary was drafted in which five potential action plans for dealing with the wreck were provided i) Removal, ii) Entombment iii) Containment iv) Continuation of monitoring, or v) Do nothing. Since the creation of this action plan, to the author’s knowledge, no further action has been taken and no further studies have been made into feasibility of carrying out any of the actions.

The 2009 survey by the MCA was assisted by Wessex Archaeology. Wessex Archaeology reviewed survey data from the 1970s up to the current survey and looked at historical Liberty Ship data. Regrettably, this report was not publicly released and the only inclusion of its content within the MCA 2009 report was a remark on the structural weakness of the build of Liberty Ships.

On the 18th March, 2013, a team of divers surveyed the wreck for the first time in a decade. The results of this survey have not yet been made publically accessible.

3.2.5 Montgomery in the news

Due to the sensitive nature of the wreck of the Richard Montgomery a large part of the management of the site involves raising public awareness and providing accurate information. This comprises informing the public as to the safety of the wreck, but also ensuring that information is not misconstrued into over-exaggerated scare-stories. Therefore, how the wreck has been depicted in the news and received mention within the UK Parliament is considered here as part of the site management.

One of the first news articles describing the wrecking event, released on 21st August 1944 in the ‘Kent: a chronicle of the century’ (Ogley, 1944), using just 153 words, painted a sinister picture of how the wreck “could easily wipe [Sheerness] off the map of Kent” and paved the way for a seventy year long series of news articles which echoed the fear-mongering themes of this article.
Figure 3.10: a) Trends of the search terms SS Richard Montgomery (Blue line), Thames Estuary Airport (Black line) and the London Gateway Port (Red line). Values are of search term interest relative to highest point on chart. Search performed using Google Trend on 05/08/2014. b) Timeline of article headlines featuring the ‘SS Richard Montgomery’, search performed using lexisnexis.com. c) Stacked bar graph of mentions of the ‘SS Richard Montgomery’ within UK Parliamentary meetings. Search performed using Hansard.millbanksystems.com (1944 - 2005) and parliament.uk (2005 - present).
The wreck was first referred to as “The Doomsday Ship” in the Wide World magazine Autumn 1964 (Lampe, 1964). In his article, Lampe employed the expertise of “Britain’s most famous and world’s most experienced bomb disposal expert” (Lampe, 1964, p.225), A.B. Hartley, who’s conservative forecast suggested that were the wreck to detonate all 14,000 residents of Sheerness would be “destroyed” (Lampe, 1964, p.226).

The wreck’s presence in the eye of the public can be traced using trends of internet search terms (Figure 3.10a), searching for newspaper articles featuring the Richard Montgomery (Figure 3.10b) and by mentions within UK Parliamentary meetings (Figure 3.10c). By far the largest peak in internet users’ interest coincides with the August 2004 New Scientist publication ‘The Doomsday Wreck’ (Hamer, 2004), published exactly 60 years after the wrecking event and echoing the title of the Lampe (1964) article. Following this little activity is observed until December 2006, coinciding with the showing of the BBC’s Coast: From Felixstowe to Margate. Since its airing interest has remained more stable and closely maps the public’s interest in the Thames Estuary Airport and the London Gateway Port (locations shown in Figure 3.1). The latter was constructed from 2010 - 2013 and is positioned just over 10km upstream of the wreck. However, container ships must pass within 2km of the wreck, resulting in fears that bow waves from these vessels may disturb the wreck (HR Wallingford, 2013). Several locations have been proposed for the Thames Estuary Airport, the site most commonly referred to as Boris Island (named after then Mayor of London) lies well to the east of the wreck site. However, the currently favoured location on the Isle of Grain, referred to as Thames Hub, lies just 3km west of the site. Both the construction of the airport and its usage pose risks to the stability of the site (Airports Commission, 2014), hence the correlated levels of interest.

The public’s level of concern with regards to the wreck is temporally sporadic and is often incited by another rehash of the same story, or as Lloyd’s List Magazine describe it “the annual Richard Montgomery story” (Lloyd’s List, 2007). On occasion this has spurred individuals to create online petitions (e-petitions) for the removal/rendering-safe of the wreck. One such petition, which closed in 17/08/2012, attracted 224 signatures (http://epetitions.direct.gov.uk/petitions/13021), well under the 100,000 threshold for the subject to be considered to be debated in the House of Commons. The subject has, however, been raised within UK Parliamentary meetings at least 45 times from 1952 - 2014 (Figure 3.10c), many of these occasions relate to accessing survey reports as well as concerns with regards to the safety of the wreck and the effects that dredging and shipping activities may have on the wreck.
3.3 Site conditions and stability

The present day conditions at the site are now considered using fourteen multibeam bathymetric surveys (from 1995 - 2012). Also quantified are the primary drivers of processes at the site which may lead to its long-term stability or deterioration.

![Figure 3.11: Bathymetry from 2012 survey, with locations of transects, ambient areas and the area designated as the scour extent. The simplified rectangular scour extent has meant that there is overlap between the ambient areas and scour extent, though the ambient areas are not exposed to scour processes (data courtesy of MCA).](image)

3.3.1 Environmental conditions

3.3.1.1 Geological conditions

The wreck of the *Richard Montgomery* is located on the Sheerness Middle Sand bank between the Thames channel (to the north) and Medway channel (to the south). The wreck lies at a maximum depth of 20m (relative to CD, Sheerness) (Figure 3.11). Sheerness Middle Sand bank is comprised of Holocene fine sands, with a median grain size of 0.14mm (*Medway Ports, 1998*), atop a base of Quaternary Terrace gravels and below that an erosion-resistant layer of Tertiary bedrock, London Clay (*Halcrow Group Limited,*
Under the classification system used in Dyer and Huntley (1999) Sheerness Middle Sand would likely be classified as a type 2A bank, a flow aligned, ridge-shaped bank, located within an estuary mouth. Type 2A banks generally migrate away from the steeper face. However, even the earliest charts of Sheerness Middle Sand date from a time where human interference will have shaped the sedimentary environment (through dredging activities etc.).

### 3.3.1.2 Metocean conditions

The Outer Thames Estuary is a macro-tidal estuary with a spring tidal range of 5.2m and a neap tidal range of 3.2m (Tidal Diamond C, Admiralty Chart 3683; United Kingdom Hydrographic Office (UKHO), 2012). Tidal diamond data indicate that the site is exposed to a flood dominant tidal current (flowing towards the west southwest, 248 - 257° True) (Figure 3.12a). In good agreement, current meter data indicate the tidal velocity vectors are aligned 71°T(ebb)/244°T(flood), with a maximum velocity at 3m above the seabed of 1.00m/s in both the flood and ebb direction, averaging 0.5m/s over the cycle (based on data from a July/August 1998 deployment of a current meter C. 25km east-north-east of the site) (Figure 3.12b). Measurements taken from an observational platform 9km north-east of the site recorded depth averaged flood velocities of 0.44m/s in comparison to ebb velocities of 0.30m/s (Whitehouse, 1995). Whitehouse (1995) observed no significant increase in the suspended sediment concentration during the ebb tide and found that sediment only became suspended at depth averaged velocities greater than 0.3m/s (a critical shear velocity ($u^*$) threshold 0.027m/s), which were only maintained during the flood tide (for approximately 4 hours). In close agreement with the platform measurements, float tracking measurements taken directly over the wreck site indicated that peak surface flood velocities were 0.15m/s faster than peak ebb velocities (Hydraulics Research Station Wallingford, 1971).

The site is predominantly exposed to waves approaching from the east-south-east and west-south-west (Figure 3.13). Mean significant wave height ranges from 0.30m in the summer to 0.34m in the winter and significant wave height peaks at 1.6m in the winter. The mean wave period is 2.1s across both summer and winter.

As wave buoy data are restricted to the second half of the survey period (2002 - 2012), sea-level elevation data from the Sheerness tide gauge, less than 4km southwest of the wreck site, are used to cover both the first half of the survey period as well as to determine how typical or atypical the storminess of the survey period was in comparison to the prior decades. Using this elevation series the difference between the maximum recorded sea level during a tidal cycle and the predicted maximum tidal level for that cycle, 'skew surge', was determined following the methodology of Wadey et al. (2014). This parameter describes the storm surge component of the series and when combined
Figure 3.12: a) Tidal rose of spring flood and ebb velocities (data from Tidal Diamond C, UKHO Admiralty Chart 3683). b) Current velocity and direction, 3m above the seabed, for 01/04/1998 (Eulerian current meter)

with the Environmental Agency’s (EA) national extreme value statistics gives the return period for storm events (Mcmillan et al., 2011). During the 17 year survey period there have been 15 occurrences of a ≥ 1 in 1 year storm, closely conforming to the average storm exposure. However, no storms above the 1 in 5 year threshold were observed. The largest number of storms between surveys happened between 2000 and 2002, where 5 storms occurred. The largest storm on record occurred outside of the survey period on the 10th December 1965 and had a sea-level height of 7.01m above CD, in comparison to the greatest storm observed during the survey period of 6.72m which occurred on the 16th December 2005. Conclusions made about the stability of the site are only valid inside of the environmental conditions witnessed during the observational period, i.e the effects of a greater than 1 in 5 year storm are unknown.

Using linear wave theory (Li and Amos, 1995) for average wave conditions skin friction shear velocity at a depth of 5m (the average depth atop the bank) is <0.001 m/s, whereas during storm conditions (of significant wave height 1.6m and periods of 2.3s) skin friction shear velocity is estimated to peak at 0.008m/s, which is below the critical shear velocity for initialisation of bedload transport, of 0.011m/s. Under combined storm and ebb tidal flow, combined total shear velocities are modelled to reach 0.017m/s and thus supersede the threshold for transport. Therefore, under this scenario, sediment is only likely to be mobile during the ebb phase, towards the east-north-east, during storm conditions.

Using crest-crest migration and by calculating the bedform asymmetry ratios the predominant bedform migration direction and rate across the site were determined, giving an indication of the bedload sediment transport pathways (Cazenave et al., 2013; Knaapen, 2005) (Figure 3.14). The area surrounding the wreck is comparatively featureless, which conforms with the prediction that the ambient current velocities are insufficient to cause
significant sediment transport. Therefore, upstream of the structure velocities are insufficient to transport sediment and only in the region hydrodynamically altered by the presence of the structure does transport occur (clear-water conditions).

Isolated areas of bedforms are, however, observed and are described here using standard nomenclature (Ashley, 1990). Large amorphous subaqueous dunes (wavelengths $\approx 20$ m,
heights $\approx 0.6\text{m}$, asymmetry ratio 1.4) are found to the north of the site in the swatchway, below the 10m depth contour, these bedforms migrate westerly at a rate of 0.5 - 2m/yr. Similarly, asymmetrical, south-westerly traversing medium dunes (wavelengths $\approx 10\text{m}$, heights $\approx 0.2\text{m}$, asymmetry ratio 1.4) are observed within the dredged channel to the south, these migrate by just 0.1 - 0.15m/yr. Both these areas of bedforms likely result from the net south-westerly tidal current across the site. Symmetrical, non-migratory, wave-induced bedforms (wavelengths $\approx 7\text{m}$, heights $\approx 0.2\text{m}$, asymmetry ratio 1.1) are confined to the shallow areas (depths of 2 - 7m) on the flank of the bank to the south-west of the site. The only area of the site where we observe easterly migrating bedforms is on the lip of the scour pit to the east of the mid-section. Due to the close proximity of these small dunes (wavelengths $\approx 6\text{m}$, heights $\approx 0.2\text{m}$, asymmetry ratio 1.5) to the structure it is likely these are formed by changes in the flow regime, inducing counter-flowing horse-shoe vortexes.

The hydrodynamic conditions described above suggest that there is limited advection of material in the area surrounding the scour pit.

### 3.3.2 Time-series: Historical charts

An understanding of the multi-decadal stability of the site is useful when determining the effects of the hydrodynamic environment on the sediment transport regime at shorter time scales (multi-annual). By digitising historical charts (1924 - 1992) of the Sheerness approaches (Admiralty chart number 3683) using ArcMap v.10.2 the change in the location of depth contours with time can be mapped (Figure 3.15), describing both the spatial evolution and potential accretion/erosion of the bank.

Historic charts were georectified following the procedures outlined in Chapter 2, Section 2.2.9; i.e. moving from youngest to oldest. Georeferencing-associated Root Mean Squared (RMS) values of between 10 - 38m were achieved (mean RMS of 21m), this value describes the accuracy of the transformation alone.

The 6.25m (1924 - 1930, 1992)/6.3m (1937 - 1969) below CD contour was selected as this contour describes the edge of the bank and is present in most historical charts (with the exception of 1908, not included here). The geometric centre (centroid) of this contour for each year was calculated; from this the position of the contour and thus the movement of the bank can be observed (Figure 3.15).

On average the bank centroid migrated 10m per year. The smallest rate of centroid displacement is from 1937 to 1948, at a rate of $<1\text{m/yr}$. Differences in the depth contour width and area indicate that two charts represent different sounding surveys, though the 1948 chart is an update of the 1943 chart and so it is likely that the 1948 chart displays soundings from 1943 or even earlier, which would account for the exceptionally small movement of the bank contour over this period of time.
Figure 3.15: Sheerness Middle Sand bank depth contours of 6.25m and 6.31m for 1924 to 2008, overlain on the 2008 bathymetric surface (data courtesy of UKHO and Medway Port Authorities). Warmer colours designate older depth contours and cooler colour more recent contours. Every other contour for charts with major corrections displayed for clarity. ‘X’ marks the location of the centroid of each contour. Note the proximity of the location of dredged channel to the south of the wreck site, which at the survey time had been deepened to a minimum depth of 12.5m.

Net movement of the 6.25/6.3m contour from 1924 to 2008 is just 57m (15m west and 55m south). Over the same period of time the contour narrowed by 24m and decreased in area by 67,000m². Considering a total positioning error of ±79m (maximum georeferencing-RMS, sextant positioning and plotting position), then the net migration of 57m could potentially be within error, i.e. there has been no detectable change of the bank’s position over the 84 year period.

There are two mechanisms by which the bank may have maintained its position and height: i) there has been virtually zero sediment transport, i.e. the current velocities at the site are insufficient to transport sediment, or ii) there is a balance in the net removal and net gain in sediment from the system, i.e. the sediment is mobile, however, there are mechanisms that return the same amount of sediment to the system as is removed by advection. Sediment mobility is considered further within the later section of multibeam bathymetry time-series (Section 3.3.3.4).

As estuarine sedimentary features have been shown to be sensitive to the removal of sediment through dredging (Thomas et al., 2002), the dredging record of the Medway Approaches has been compared with the historical chart analysis.
The first recorded capital dredging (dredging virgin material for the purpose of creating a navigable channel) of the Medway Approach Channel (location can be seen in Figure 3.15) occurred in 1952, where the channel was dredged by approximately 0.2m to a minimum depth of 8.5m \textit{(Institute of Estuarine and Coastal Studies (IECS), 1993)}. Siltation meant the channel was dredged again in 1972, removing 0.5m depth of material in some places. Following this campaign the channel depth became self-maintaining and maintenance dredging was not necessary until 1989. Following this in 1990 the channel was deepened to 11m and finally in 2001 it was deepened a further 1.5m to a minimum depth of 12.5m in order to allow access to the expanding Thamesport. In-between these capital dredging campaigns maintenance dredging to maintain the depth of the channel took place. Dredging during the survey period occurred in 2001, 2002, 2003, 2004, 2005, 2007, 2009, 2010 and 2012. Material dredged from the Medway Approach Channel is deposited over 45 nautical miles away at an offshore site \textit{(Institute of Estuarine and Coastal Studies (IECS), 1993)} and so is entirely removed from the system. A total of 335,528 m$^3$ of material was removed from the channel between 2001 and 2005.

The morphological stability of Sheerness Middle Sand as observed using historical charts even after dredging activities suggests that the dredging of the Medway Approach Channel has no significant impact on the sediment transport system of the sand bank. Using the time-series of multibeam bathymetry, bathymetric surveys just one year either side of dredging events will also be considered within the next section.

\section*{3.3.3 Time-series: Multibeam bathymetry}

\subsection*{3.3.3.1 Methods and materials}

Swath bathymetric data for both the wreck and for the surrounding area \textit{(the greatest coverage was 0.8km$^2$ in 2012)} were collated for the years given in Table 3.2. Bathymetric data were provided in an xyz text format, with tidal corrections already applied and in a pre-interpolated, 0.4 $\times$ 0.4m, geometric grid \textit{(with the exception of the 2002 - 2012 data, which were interpolated before being sampled onto the same grid as the 1995 - 2000 data)}. Data were displayed and manipulated using ArcMap v10.1.

To construct bed-level change plots, bathymetric layers were subtracted from one another. Scour depths are given relative to a filled average bathymetry surface \textit{(used as an approximation of the pre-wreck installation surface, the method for which is given in Chapter 2, Section 2.1.3.3)}. The average surface is a mean of all fourteen bathymetry surveys.

For ten of the surveys \textit{(1995 - 2000, 2009 - 2012)} the data were provided pre-corrected to CD, Sheerness and one dataset \textit{(2005)} in ETRS89. However, three of the datasets \textit{(2002, 2006 and 2008)} appeared to have a static offset relative to CD. In order to determine this vertical offset the ambient bed-level change between entire surveys was calculated \textit{(Table 3.2, areas designated as ambient shown in Figure 3.11)}. For the years of 2002, 2006
and 2008 there were clear static offsets of 5m, 1m and 0.6m respectively, and so these were corrected for accordingly. The resultant ambient bed-level change values all fell within a range of ±0.3m, well within the vertical uncertainty of the International Hydrographic Organisation’s (IHO) standards for order 1a surveys of ±0.5m (International Hydrographic Organisation (IHO), 2008).

### 3.3.3.2 Present-day (2012) site morphology

The localised modified flow around the wreck structure has carved an asymmetrical (elongated in the direction of the flood tide), triple-lobed scour feature (Figure 3.11). The central lobe, formed due to the gap between the two hull sections (effectively creating two distinct structures), is shorter in length (on average over the time-series 130m long) and narrower (50m wide) than the two lobes emanating from the north and south of the structure (on average 280m and 180m long, and 80m and 60m wide, respectively). The entire area of the scour pit is approximately 4,600m$^2$, potentially equating to 180,000m$^3$ of removed material relative to the ambient bed-level.

Relative to filled average bathymetry the average maximum scour depth was $-11.6$ m. Maximum scour depths were 1.8m and 0.4m shallower within the central lobe and south lobe, respectively, than within the north lobe.

The highly asymmetrical, multi-lobed scour pit morphology is interpreted as having been formed by a steady asymmetrical flow with the prevailing current direction at an angle of 45 to 90° relative to the wreck (Saunders, 2004), supported by metocean data which indicated that the tidal regime is sufficiently asymmetrical as to create a regime which during non-storm conditions only allows for sediment transport during the flood phase.

Within the scour pit a maximum slope angle of 37.4° and a median slope angle of 9.9° were recorded, in comparison to an ambient maximum slope of 6.2° and median slope of 2.7°. The maximum slope angle of a scour hole is comparable to the dynamic angle of repose of the bed material (Melville, 1975), which for fine sand in water is approximately 26 to 34° depending on its compaction (Hoffmans and Verheij, 1997). Slope angles above the dynamic angle of repose were observed at the very edges of the scour hole and may be a result of dilatancy effects associated with fine sands with relatively low permeability as described by van den Berg et al. (2002).

### 3.3.3.3 Results

Bed-level change plots (Figure 3.16) show spatial heterogeneity in the temporal bed-level change between surveys; throughout the time-series there are relatively few areas which undergo consistent year on year trends of bed-level loss or gain. Instead we observe
Table 3.2: Details of bathymetry surveys and corrections applied to account for vertical offsets between surveys. Locations of ambient areas are displayed in Figure 3.11.

<table>
<thead>
<tr>
<th>Survey year</th>
<th>Survey month</th>
<th>Sonar system Positioning system</th>
<th>Vertical offset</th>
<th>Ambient bed-level change with vertical offset applied</th>
<th>Survey month</th>
<th>Survey year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>July</td>
<td>V/N</td>
<td>&quot;</td>
<td>&quot;</td>
<td>October</td>
<td>2012</td>
</tr>
<tr>
<td>1996</td>
<td>September</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>November</td>
<td>2011</td>
</tr>
<tr>
<td>2000</td>
<td>June</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>June</td>
<td>2000</td>
</tr>
<tr>
<td>2002</td>
<td>August</td>
<td>V/N</td>
<td>&quot;</td>
<td>&quot;</td>
<td>August</td>
<td>2002</td>
</tr>
<tr>
<td>2005</td>
<td>September</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>September</td>
<td>2005</td>
</tr>
<tr>
<td>2006</td>
<td>August</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>July</td>
<td>1996</td>
</tr>
<tr>
<td>2008</td>
<td>October</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>August</td>
<td>1998</td>
</tr>
<tr>
<td>2009</td>
<td>October</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>July</td>
<td>1999</td>
</tr>
<tr>
<td>2010</td>
<td>June</td>
<td>V/N</td>
<td>&quot;</td>
<td>&quot;</td>
<td>July</td>
<td>2010</td>
</tr>
<tr>
<td>2011</td>
<td>November</td>
<td>Reson 8125</td>
<td>IARTK</td>
<td>&quot;</td>
<td>November</td>
<td>2011</td>
</tr>
<tr>
<td>2012</td>
<td>October</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>October</td>
<td>2012</td>
</tr>
</tbody>
</table>
Figure 3.17: Transects of elevation relative to CD. Every other survey given for clarity. Locations of transects shown in Figure 3.11.
Table 3.3: Net, maximum positive and negative bed-level change within rectangular scour extent (extent displayed in Figure 3.11).

<table>
<thead>
<tr>
<th>Time period</th>
<th>Net bed-level change (m)</th>
<th>Maximum negative bed-level change value (m)</th>
<th>Maximum positive bed-level change value (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995 to 1996</td>
<td>−0.1</td>
<td>−2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>1996 to 1997</td>
<td>0.0</td>
<td>−0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>1997 to 1998</td>
<td>−0.1</td>
<td>−1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>1998 to 1999</td>
<td>0.0</td>
<td>−1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>1999 to 2000</td>
<td>0.0</td>
<td>−0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>2000 to 2002</td>
<td>0.0</td>
<td>−2.5</td>
<td>1.1</td>
</tr>
<tr>
<td>2002 to 2005</td>
<td>−0.3</td>
<td>−1.9</td>
<td>0.9</td>
</tr>
<tr>
<td>2005 to 2006</td>
<td>0.1</td>
<td>−0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>2006 to 2008</td>
<td>0.1</td>
<td>−1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>2008 to 2009</td>
<td>0.1</td>
<td>−0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>2009 to 2010</td>
<td>−0.3</td>
<td>−1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>2010 to 2011</td>
<td>0.2</td>
<td>−0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>2011 to 2012</td>
<td>−0.1</td>
<td>−0.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure 3.18: Bed-level change plot for 1996 to 2012 (1996 used instead of 1995 as it covered a much larger area). Blue areas indicate bed-level loss, erosion and red areas bed-level gain, accretion. Cream colour areas indicate areas where bed-level change is within the vertical uncertainty of the data. Wreck structure bathymetry from 2012 survey. Data courtesy of MCA.
patches of bed-level loss and patches of bed-level gain confined primarily to the triple-
lobed scour feature, but with no discernible temporal trend. On the whole there are lim-
ited areas of the scour pit exempt from statistically significant bed-level change between
surveys.

The confinement of the majority of the bed-level variability to the scour pit is captured
well by transects of bed-level (Figure 3.17). Transect A (Figure 3.17a), which bisects the
northern scour lobe, highlights an increase in the bed-level, of approximately 1.0m from
1995 - 2012, confined to areas of high curvature (areas of high rates of slope change) on
both the upstream and downstream (relative to the flood tide) sides of the scour pit. The
only area which appears to have undergone bed-level accumulation across the time-series
is 50m upstream of the north and the mid-sections of the structure (Figure 3.17a,b).
Here, over 3.5m of gain over the seventeen year period is observed. The southern scour
pit is the most stable of all three lobes, a range of $\pm 1$m is observed over the entire time-
series.

From 1999 onwards a spiral-like feature appears within the central downstream lobe (Fig-
ure 3.16d - m, Figure 3.17b, d). This feature appears to be largely erosive and revolves in
an anti-clockwise direction. This feature is topographical separated from the main scour
pit by a ridge 3m high.

Maximum negative and positive values of yearly bed-level change for the scour pit were
within the range of $-2.5$m/yr to 1.7m/yr (Table 3.3, Figure 3.20b). These values are an
order of magnitude greater than the maximum negative and positive bed-level change val-
ues associated with the ambient areas (locations shown in Figure 3.11), which fell within
a range of $\pm 0.9$m/yr.

There was a much larger range of bed-level change values within the scour pit for the
periods of 1995 - 1996 ($\pm 2.0$m), 2000 - 2002 ($\pm 2.5$m) and for 2002 - 2005 ($\pm 1.9$m) than
for the other years ($\pm 1.2$m). There is no apparent temporal trend in bed-level change
(Table 3.3, Figure 3.20b). Despite maximum bed-level change values of several metres
per year, average values for the area for were all within the range of $-0.3$ and 0.2m. The
total net bed-level change for the seventeen year period was $-0.6$m (Figure 3.18). This
small but negative value is strongly controlled by the more negative net bed-level change
values during the periods of 2002 - 2005 and 2009 - 2010. Excluding these two periods, as
the ambient bed-level change vertical error is exceeded for 2002-2005 and almost met for
2009-2010 (Table 3.3) and so the data are suspect, gives us a total net bed-level change
over the time-series of effectively zero.

Maximum scour depths are found on the downstream (relative to the dominant flood
tide) side of the northern section of the wreck for all years (Figure 3.19) with the ex-
ception of 1996 and 2005 where maxima were located on the upstream side of the mid-
section and downstream side of the southern section, respectively. Relative to the filled
surface (representative of a pre-scour surface) these scour depths are in the range of 9.9
Figure 3.19: Locations of maximum scour depth for each survey, overlaid on an average bathymetry surface with depths relative to the filled average surface. All maximum depths are in the same location, with the exception of 1996 and 2005.

- 12.1m (Figure 3.20a). The close proximity of the maxima for 12 out of the 14 surveys (all within 9m$^2$ of one another) suggests that the scour hole is stable on a time scale of years. The exceptions of 1996 and 2005 are likely to result from the small difference in scour depth between the downstream north, south and upstream midsection as described in Section 3.3.3.2. Maximum scour depth within the northern downstream scour pit for these two years are less than 0.1m shallower than the maximum depths. Maximum scour depth increased from 1995 to 1996 by 1.5m, after which it plateaued at a rate of $-0.05\pm0.03$m/yr (Figure 3.20a).

### 3.3.3.4 Discussion

During the survey period the site was exposed to numerous storm events, with wave heights greater than 1.3m at Maplin (7km northeast of the wreck, location shown in
Figure 3.20: Time-series of a) Maximum scour depth for each survey, relative to averaged filled surface. Error bars of the vertical uncertainty of the data (±0.3m) b) Box and whisker plots of bed-level change, plus signs mark the locations of the mean values c) Significant wave height for Maplin (blue) and Herne Bay (red), arrows of events with significant wave heights above the storm threshold and d) Sea-level elevation from Sheerness tide gauge above CD; arrows of skew surge storm events above the 1 in 1 year threshold. Vertical grey lines indicate dates of surveys.
The storminess of the site can also be observed through analysis of the skew surge record extracted from the Sheerness tide gauge record following the methodology of Wadey et al. (2014) (Figure 3.21). From this record (1952, 1958, 1965 - 75, 1980 - 2012) we observe
a peak in storminess in the early 1980’s and mid 1990’s. The only storm over the 1 in 10 year threshold to have been observed at this site occurred in 1965. There have been four 1 in 5 year storms since the 1950’s, but just one during the multibeam bathymetry surveying period in 1996.

All multibeam bathymetry surveys were performed between the months of June and November; no surveys were carried-out during the spring and winter months. However, this does not prevent us from projecting how the site may be behaving during these periods of time. Year-on-year the bed-level of the area surrounding the wreck either maintains, or returns to the same level, within vertical uncertainty (Table 3.3). Even when the site has been exposed to a significant storm event just days before surveying, such as in 2010, where waves with significant heights of 1.6m were observed at the Herne Bay gauge less than a month before the survey was carried out, the site undergoes very little change in comparison to the previous year’s survey. During the survey no storm events of greater than a 1 in 6 year storm were recorded at the Sheerness tide gauge station. Therefore the trends seen in this dataset may change for periods of larger storms.

The large standard deviation of the 1995 data could be indicative of vertical inaccuracies in the 1995 data which could be accounted for by differences in tidal conditions, meteorological conditions or instrumental precision. In the year leading up to the 1995 survey only a single 1 in 1 year storm occurred. Meteorological conditions are unlikely to be the source of this error. The large range of bed-level change values for 2000 - 2002 and 2002 - 2005 are likely to be due to errors associated with the collection and processing of the 2002 data as this was a trial year for the new Reson sonar technology (Maritime and Coastguard Agency (MCA), 2005).

The downstream erosive feature, first observed in 1999, is likely to be a result of the gap between the two sections of the hull. Similar flows have been observed downstream of two cylinders side-by-side (Meneghini and Saltara, 2001). In physical and computational models Von Karman vortex streets are generated downstream of each cylinder, which when squeezed, amalgamate with the outer vortices creating a semi-permanent vortex. The larger negative bed-level change values found in the area of the central downstream scour feature could indicate an increased flow, in the direction of the flood tide, through the break in the hull. However, surveys do not indicate that this gap has widened over the seventeen year observation period and so, this is not likely to be the cause of this scouring. The lip of the scour pit upstream of the break between the hull sections was observed to be an area of frequent modification (i.e. from 1997 - 1998 it eroded and during 1997 - 1998 sediment accumulated here). This could potentially have altered the flow through this gap and thus the resultant downstream scouring. Without modelling (either physical or computational) this hypothesis cannot be confirmed.

The initial decrease in maximum scour depth from 1995 to 1996 is likely to be associated with the vertical inaccuracies of the 1995 data discussed above. In order to attain the
present day scour depth of 12.1m scour rates must have been greater during some previous period of time. It is likely that a large portion of this scour occurred during the initial few hours to weeks (McGovern and Ilic, 2014), although this cannot be confirmed as no high-resolution bathymetry surveys were performed during this period of time.

As was observed within the historical chart record, the change in bed-level shown by the bathymetric time-series does not appear to be heavily influenced by the dredging activates of the Medway Approach Channel. For example in 2001 there was a capital dredging campaign and yet effectively zero bed-level change occurred from 2000 to 2002. There could, perhaps, be a delayed response resulting in the bed-level loss observed from 2002 to 2005, though this would be a difficult hypothesis to test. In a study of the effects of dredging on physical changes in estuarine sediments Sollitt and Crane (1974) observed an initial recovery phase during the first two weeks and no further recovery over the following two months. It was proposed that the initial recovery resulted from the availability of local sources of sediment, but that complete recovery would require a larger source of sediment most likely from increased runoff during winter/spring months. Only two storms were observed between 2000 and 2002 (Figure 3.20c), in comparison 5 were observed between 2002 and 2005. Therefore, the recovery could be as a result of additional storm activity.

It is reasoned that the resultant statistically insignificant bed-level change, yet metre-scale range of bed-level change values, results from a containment of the transport of sediment to within the bounds of the scour pit, under a regime similar to that described by McGovern and Ilic (2014). The reworking of sediment indicates that the bed is still mobile within the scour pit, but the morphology of the pit and the near balanced bidirectionality of the hydrodynamic regime prevent the temporal net export or import of material.

3.4 Implications for cultural heritage management

3.4.1 Containment of material

Equipped with both an understanding of the site morphology and sediment transport processes, artefact-scale transport processes are now considered. In the instance of the Richard Montgomery the predominant class of artefacts of concern are the near 10,000 explosive devices and over 4,000 boxes and cases of devices (Defence Evaluation and Research Agency (DERA), 1997).

Within multibeam bathymetry data (1995 - 2012) no targets are observed outside of the 3000m² outline of the wreck that can be positively identified as having originated from the wreck. Using the same multibeam bathymetry instrument (Reson 8125) as used in the 2002 - 2009 and 2011 - 2012 surveys of the SS Richard Montgomery, Bates et al.
Richard Montgomery (2011) were able to detect metallic objects with diameters as small as 0.5m. Therefore, even the smallest explosive devices (not packed within metal-lined cases), 250 lb AN M57’s, with dimensions 1.1m x 0.9m x 0.3m, should be detectable within the multibeam bathymetry surveys.

This absence of surface targets is surprising considering there are many other users of the estuary and thousands of munitions have been dropped upon the Thames and dockland, including an estimated 15,000 high-explosive bombs, 250 parachute mines, 550 flying bombs and 240 rockets over the course of the World War II (WWII) raids (Ackroyd, 2009). In addition to this there are reports of fishermen disposing of bombs, which they accidentally hooked in their nets, onto the site (Atkinson et al., 1972) and so there is significant potential contamination of the record.

Whilst no munitions are believed to have left the holds of the wreck, the 2000 risk assessment of the Richard Montgomery stated that by 2020 - 2030 munitions currently contained within the hull would become dispersed (BMT Reliability Consultants Ltd, 2000).

\[ F_T = \mu_k \rho_s - \rho \cdot g m_b \cos \beta \]
\[ W_x = \rho_s - \rho \cdot g m_b \sin \beta \]

Figure 3.22: A free-body force diagram of a cylinder (bomb) on a slope. Where \( F_{App} \) is the applied force up the slope, \( F_T \) is the frictional force working in opposition to the applied force and \( W_x \) is the immersed weight of the cylinder acting down the slope. Where \( \mu_k \) is the friction coefficient, \( \rho_s \) is the density of the cylinder, \( m_b \) is the mass of the cylinder and \( \beta \) is the angle of the slope. For a threshold of transport scenario these three forces would balance.

Continuing this dispersal scenario, the consultants also used a basic forces balance (Figure 3.22) to determine whether or not local velocities are sufficient to transport munitions up the sides of and out of the scour pit. In this report it was stated that for munitions of size 100lb and incendiary devices of 4lb, the threshold for transport out from the scour pit are 0.4m/s and 0.35m/s, respectively. Velocities exceeding these thresholds are frequently observed at the site. However, these values were calculated for the shallowest slope of the scour pit, a 1 in 36 slope (2.8% or 1.6°) and there are no pathways for munitions to leave the scour pit where they would encounter angles of less than 1.6° the entire route (Figure 3.23). Therefore, the velocity thresholds calculated are likely to be an underestimation. Furthermore, this simplified scenario does not take into account: localised variations in the seabed slope, the potential different types of transport depending
on the bomb’s orientation (e.g. rolling or sliding) or the importance of a continual flow in order to extract the bomb from the scour pit. A study addressing all of these factors is well beyond the scope of this thesis. However, the results of the BMT Reliability Consultants Ltd (2000) force-balance study on the dispersal of munitions, the physical target identification using bathymetric data and self-containment of sediment within the scour area observed through the time-lapse bathymetry dataset all indicate that the dispersal of munitions out from the scour pit is unlikely.

Another pathway that munitions may take, not yet tackled within this study, is burial into the sediment. The settling of uncontained munitions into the surrounding sediment could explain why no artefacts are seen in the surrounding area. This effect has been observed at wreck sites where artefacts have gone through settling-exposure cycles (McNinch et al., 2001). Another approach is through the physical modelling of the burial of cylinders, ordnance and mines. We do not expect any burial through impact driven processes, since the munitions were carried to the seabed within the hull of the ship. Therefore, we are concerned only with settlement by consolidation or creep or burial via bedform migration or scour (Wilkens and Richardson, 2007). Bedforms are not observed within the scour pit. Therefore, burial is only likely via consolidation or creep or scour. Burial of artefacts is greater in environments with fine sand (Trembanis et al., 2007), making it likely that this process is/would happen to any munitions which would come loose from the holds. Burial would continue so long as no erosive-resistant surface was reached, which in the case of the Richard Montgomery site would be the London Clay.
3.4.2 Fate of the Montgomery

The caution applied by authorities responsible for the wreck of the Richard Montgomery when proposing and implementing management plans is not unfounded as other ships and wrecks with similar cargos to that of the Richard Montgomery have detonated, often with disastrous effects. Both the Liberty Ships, SS E. A. Bryan and SS Grandcamp, exploded whilst at berth in 1944 and 1947, killing 320 and 581 people, respectively (Sawyer and Mitchell, 1985). The SS E. A. Bryan, of the same build-type as the Richard Montgomery, exploded whilst being loaded with munitions, 4,500 tonnes detonated, destroying piers and buildings, with the blast being felt up to 200 miles away (Moore, 1993). The SS Grandcamp was also at berth when it detonated, destroying warehouses, a nearby chemical plant and other vessels. Whilst these detonations were not due to the deterioration of the munitions within a shipwreck, these examples do highlight the potential explosive capacity of cargos carried by Liberty Ships.

A more comparable scenario to the SS Richard Montgomery, often cited as the reason for the adoption of the ‘do nothing’ strategy, was the detonation of the already sunken Kielce, which exploded during an attempt at removing ammunition from the wreck in 1967. The detonation of the wreck off Folkestone, resulted in an explosion equivalent to an earthquake measuring 4.5 on the Richter scale and created a 6m deep crater on the sea-bed of the English Channel (Harper and Dock, 2007; Maritime and Coastguard Agency (MCA), 2000). The detonation occurred after explosive cutting charges were fired during an attempt to clear the wreck. The total weight of the cargo is unknown, but at a gross tonnage of 1896 (almost a quarter the capacity of the Richard Montgomery, with a tonnage of 7176) the Kielce was most likely holding a smaller explosive cargo than that of the Montgomery. The wreck was also positioned further offshore (more than 5km from the nearest land) and at a depth of 27m (5m deeper than the maximum depth at the Montgomery site), yet it was still reported to have damaged chimneys, dislodged slates and cracked ceilings. Once exposed to water most munitions explosive sensitivity is decreased (with a few exceptions e.g. phosphorus and TNT based munitions) (Defence Evaluation and Research Agency (DERA), 1997). Therefore, as the Kielce had only been submerged for 23 years it could be that the munitions were more sensitive than the ones presently held within the holds of the Richard Montgomery.

Numerous proposals for how the wreck might be dealt with have been considered, these include entombment, surrounding sediment dykes, removal or controlled explosion of the wreck, though none of these proposals have progressed further than the very early testing phases. Whilst it is agreed that the general condition of the hull is deteriorating (Maritime and Coastguard Agency (MCA), 2011) and it is observed that the surrounding bed has scoured around the wreck to a maximum depth of 12m below the ambient bed-level, the position of the wreck itself has remained relatively stable. What cannot be agreed upon is whether or not the wreck has been, and will continue, to get safer with
time (i.e. the water acts to neutralise the armaments and the sediments will slowly engulf the wreck) \cite{Rees1964} or more dangerous (i.e. the collapsing structure may release the munitions or even trigger an explosion) \cite{BMTReliability2000}.

Using a mean predicted corrosion rate of 0.09mm/year munitions would only become perforated and fully neutralized after 600 years \cite{BMTReliability2000}. Therefore, it remains likely that some, if not all, of the explosives on board are still live.

In the uninterrupted progression of scour as the scour hole becomes deeper the structure becomes less of an obstruction to flow and so the local velocities return to ambient levels, which, when there is a supply of mobile sediment leads to the infilling of the scour pit \cite{Trembanisetal2007}. Through near-annual bathymetry surveys of the site it is confirmed that the seabed surrounding the wreck is getting deeper at a rate of 0.05±0.03m/yr. However, the further scouring of the bed may be hindered by the less erosive deeper layers of sediment, in the case of the \textit{Richard Montgomery}, London Clays. The hindrance of further scour due to the presence of more erosive-resistant layers has been observed at other wreck sites, most notably the wreck believed to be \textit{Queen Anne’s Revenge} (QAR) \cite{McNinchetal2006}. Unlike the QAR, the bank system on which the SS \textit{Richard Montgomery} is positioned is very stable and so unlikely to migrate/erode away and expose the wreck. Were the main structure of the \textit{Richard Montgomery} to collapse the process of infilling would be accelerated as the wreck would instantaneously become less of an obstacle to flow. Mobile bedforms have been observed to the north and south of the site which would indicate a source of infilling sediment. However, the required fill volume would be approximately 180,000m$^3$.

In such a stable environment, where net annual bed-level loss is effectively zero and storm events appear to have little influence on sedimentary processes, a near-annual survey strategy does not provide us with any more information on the sedimentary environment than would be gained from a less frequent surveying program. This statement remains true so long as there are no changes in the conditions, e.g. reclamation of nearby sea for the construction of the airport or any structural changes to the wreck which may results in a change in the flow patterns. Also, this recommendation relies on there being limited influences from storms larger than those observed during the survey period. Therefore, if the site were exposed to a storm greater than a 1 in 5 year storm it would be advisable to resurvey the site to quantify the impact.

\section{Conclusions}

Accounts of the wrecking process of the SS \textit{Richard Montgomery} and the subsequent management show many discrepancies, even from recognised, reputable sources, such as the UKHO wreck record. This is likely due to the haste with which the wreck was initially dealt with due to the unfolding war. Through consulting and comparing numerous
sources and identifying these discrepancies the most plausible scenario for the series of events could was attained.

Presently, the wreck is exposed to a tidally driven environment, with very little wave action (maximum significant wave heights of 1.3m). The proximal area to the wreck is largely devoid of bedforms, indicating that there is limited sediment transport. Whilst the site of the SS Richard Montgomery was exposed to numerous (>20 events with a 1 in 1 year or greater return period) storm events throughout the seventeen year survey period, the only visible evidence for wave induced sediment transport is in the form of isolated symmetrical bedforms confined to the shallower regions (2 - 7m depth) of Sheerness Middle Sandbank.

A singlebeam sonar survey demonstrates initial scour formation occurred within the first decade. Historical charts indicate that, within error, Sheerness Middle Sand, on which the wreck is positioned, has been stable in its location over the last century.

Both on annual and decadal temporal scales bed-level change within the wreck scour pit is on the scale of decimetres. There are two regimes under which this temporal stability can be sustained: i) advection of material into the scour pit system is equal to advection of material out from the scour pit system, or ii) there is effectively no advection of material in to or out from the scour pit, in this instance the scour pit is described as self-contained. There is limited evidence for the advection of material from the scour pit, nor for the advection of material in to the scour pit. Furthermore, historical chart analysis indicates the multi-decadal stability of the seafloor environment, suggesting that the area surrounding the wreck undergoes little advection of material. Therefore the latter hypothesis (of no advection) is argued to be the more likely of the two.

Within the scour pit there is, however, significant localised topographic variability in terms of both erosion and accumulation (typically ±1.5m/yr, but up to ±2.5m/yr). It is proposed that the comparatively large range in bed-level change values results from transport of material contained within the spatial limits of the modified-flow regime.

Maximum scour depth deepened at a rate of 0.05±0.03m/yr across the time-series, though its location remained stably fixed to just off the downstream side (relative to the dominant flood direction) of the northern section.

Annual surveying of the site has been effective in capturing the site stability and demonstrates the predominance of prevailing conditions (tidal), rather than interspersed events (storm events), in maintaining the site’s morphology. Whilst the site’s long-term (multi-annual) stability is conducive towards a gradual decay of the site and containment of resulting fragments, the fate of the wreck of the SS Richard Montgomery ultimately lies in the hands of the MCA.
Chapter 4

Multibeam bathymetry time-series

In the last chapter it was observed that at the wreck site of the SS Richard Montgomery there was near-zero net change in bed-level surrounding the shipwreck on an inter-annual time-scale. From this result and an assessment of the environmental conditions at the site, it was concluded that over this time-scale the wreck was maintaining some semi-stable and self-regulating state. The Multibeam Echo-Sounder (MBES) time-series associated with the wreck of the SS Richard Montgomery is exceptional both in its length (spanning over seventeen years) and repeat interval (near-annual) and has allowed for a in-depth assessment of the taphonomic processes occurring at this shallow water, morphologically stable, tidally asymmetric, site. Through the presentation of four further wreck site time-series, the extent to which the Richard Montgomery site is a unique process-response system, is explored. Since long time-spanning (greater than a couple of years) repeat MBES time-series of wreck sites are rare, these four sites were selected primarily upon the length and interval of the time-series available. Fortuitously, due to the natural diversity of coastal waters, each one of these wreck sites presents a different set of environmental conditions to that of the SS Richard Montgomery and will allow for the driving factors towards this and other sites’ stability to be better constrained.

4.1 Comparison of case-study environmental conditions

The four case studies are presented in this chapter in order of decreasing similarity when compared to the wreck site of the Richard Montgomery. This evaluation is based upon the environmental conditions at each site (Table 4.1, Table 4.2 and Figure 4.1) and the impact of the wreck geometry and orientation relative to these conditions (Table 4.3). Although Table 4.1 and Table 4.2 offer a simplified description of the conditions at each of the wreck sites what can be gleaned from these tables is both the range of environmental conditions, as well as the similarities between sites. Whilst wanting to compare
### Table 4.1: Comparison of the prevailing environmental conditions at each case study wreck site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Site depth (m)</th>
<th>Geology</th>
<th>Mean Tidal velocity (m/s)</th>
<th>Tidal residuals (m)</th>
<th>Mean wave conditions</th>
<th>Combined mean Tidal and Wave velocity (m/s)</th>
<th>Morphology</th>
<th>Sediment thickness (mm)</th>
<th>Geology</th>
<th>She depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Richard Montgomery</td>
<td>-8.00</td>
<td>Stable bank</td>
<td>0.31</td>
<td>0.66</td>
<td>1.24</td>
<td>3.8</td>
<td>Mobile</td>
<td>-0.69</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Stirling Castle</td>
<td>-15.25</td>
<td>Mobile bank</td>
<td>0.75</td>
<td>0.48</td>
<td>2.5</td>
<td>5.0</td>
<td>Semi-mobile</td>
<td>-0.57</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>Burgzand Noord</td>
<td>-7.00</td>
<td>Semi-mobile bank</td>
<td>2.0</td>
<td>1.62</td>
<td>0</td>
<td>1.16</td>
<td>Featureless</td>
<td>0.11</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>Scylla</td>
<td>-20.00</td>
<td>Featureless slope</td>
<td>0.125</td>
<td>0.16</td>
<td>0.10-0.18</td>
<td>0.18</td>
<td>Stable Channel</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Algerian</td>
<td>-21.00</td>
<td>Stable channel</td>
<td>0.10</td>
<td>0.79</td>
<td>2.3</td>
<td>9.7</td>
<td>Channel</td>
<td>-21.00</td>
<td>1.72</td>
<td></td>
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</tbody>
</table>

*Note: All depths are referenced to Chart Datum (CD).*

*Scylla and Algerian data were recorded in a peak spring tide.*

*Combined mean Tidal and Wave velocity is the minimum angle between the prevailing wave shear and the direction of the ebb and flood tide.*

*The expression depth is used to denote the water depth below the Chart Datum (CD).*
Table 4.2: Comparison of peak (combined spring tidal flow and storm wave conditions) environmental conditions at each case study wreck site. Wave conditions are given for upper 0.5% quartile. Exposure parameters of fetch and sea horizon were based on the classification system of Muckelroy (1977) in which fetch is the maximum offshore fetch within 30° of the perpendicular to the coast and sea horizon is the sector within which there is more than 10km of open sea.

<table>
<thead>
<tr>
<th>Site</th>
<th>Peak Tidal velocity</th>
<th>Peak wave conditions</th>
<th>Combined peak tidal and wave</th>
<th>Site exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \bar{U} ) ( \tau_c )</td>
<td>( H_s ) ( T_z ) ( \tau_W )</td>
<td>Min. ( \phi ) Min. ( \tau_m ) ( \tau_{max} )</td>
<td>Max. fetch ( \text{Sea horizon} )</td>
</tr>
<tr>
<td></td>
<td>m/s ( \text{N/m}^2 )</td>
<td>m ( \text{s} ) ( \text{N/m}^2 )</td>
<td>( \circ ) N/( \text{m}^2 ) N/( \text{m}^2 )</td>
<td>km %</td>
</tr>
<tr>
<td>Richard Montgomery</td>
<td>0.65 0.31</td>
<td>1.24 3.8</td>
<td>0.69 37</td>
<td>0.42 1.06</td>
</tr>
<tr>
<td>Stirling Castle</td>
<td>1.5 2.02</td>
<td>2.5 5</td>
<td>0.57 20</td>
<td>2.04 2.58</td>
</tr>
<tr>
<td>Burgzand Noord</td>
<td>1.3 1.10</td>
<td>2 7</td>
<td>1.62 0</td>
<td>1.35 2.97</td>
</tr>
<tr>
<td>Scylla</td>
<td>0.46 0.11</td>
<td>3.47 6.8</td>
<td>0.91 75</td>
<td>0.20 0.98</td>
</tr>
<tr>
<td>Algerian</td>
<td>1.5 2.22</td>
<td>0.53 2.9</td>
<td>0.02 4</td>
<td>2.22 2.24</td>
</tr>
</tbody>
</table>
Figure 4.1: Observed tidal, wave and combined shear stress under prevailing and peak conditions against grain size, at each wreck site. Where $D_*$ is the dimensionless grain size (found using Equation 2.8). The curve delineates Soulsby’s critical threshold for transport. Values where the observed shear stress is above this curve represents conditions sufficient for sediment transport under ambient conditions.

Table 4.3: Wreck site geometry and alignment to prevailing current.

<table>
<thead>
<tr>
<th></th>
<th>Date of wrecking</th>
<th>Wreck length (m)</th>
<th>Wreck alignment (°)</th>
<th>Flow dir. (°)</th>
<th>Angle of attack (°)</th>
<th>Width (W) (m)</th>
<th>Height (H) (m)</th>
<th>W:H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Richard Montgomery</td>
<td>1944</td>
<td>149</td>
<td>5</td>
<td>252.2</td>
<td>67.2</td>
<td>137.4</td>
<td>10.6</td>
<td>13</td>
</tr>
<tr>
<td>Stirling Castle</td>
<td>1703</td>
<td>51</td>
<td>280</td>
<td>20</td>
<td>80</td>
<td>50</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>Burgzand Noord 11</td>
<td>1650</td>
<td>19.7</td>
<td>48</td>
<td>90</td>
<td>42</td>
<td>13</td>
<td>1.2</td>
<td>11</td>
</tr>
<tr>
<td>Algerian</td>
<td>1916</td>
<td>105</td>
<td>71</td>
<td>65</td>
<td>6</td>
<td>11.0</td>
<td>2.0</td>
<td>11</td>
</tr>
<tr>
<td>Scylla</td>
<td>2004</td>
<td>113</td>
<td>226</td>
<td>135</td>
<td>91</td>
<td>113</td>
<td>8.5</td>
<td>13</td>
</tr>
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</table>

*Note: Flow dir. refers to the prevailing direction of the current. W:H refers to the width-to-height ratio.*
the taphonomy of wreck sites exposed to a range of environmental regimes, it is also important to keep the majority of the site properties similar to ensure the comparison can focus on individual elements (e.g. the impact of wave exposure, grain size or tidal current strength). Comparisons between thresholds for transport ($\tau_{cr}$) and bed shear stresses ($\tau_c$, $\tau_W$, $\tau_m$ and $\tau_{max}$) (Figure 4.1) can give a general idea as to the predominance of wave or tidal forces at the sites and whether or not conditions support live bed ($\tau_m > \tau_{cr}$) or clear water ($\tau_m < \tau_{cr}$) conditions.

Through empirical studies it has emerged that on average submerged obstacles (pipelines, monopiles etc.) enhance bed shear stresses by a factor of four (Whitehouse, 1998). Computational Fluid Dynamics (CFD) models of a wreck site using a MBES derived surfaces for the fixed seabed surface confirmed this four-fold amplification of shear stresses (Smyth and Quinn, 2014). Taking this into consideration, under ambient mean tidal and wave conditions, sediment transport at the area surrounding the wreck structure is expected to occur at all sites, with the only exception being the Scylla. It is this amplification of bed shear stresses which initiates the process of sediment removal at the base of submerged structures, termed scour. Physical modelling has shown that scouring and depositional processes around wreck structures is proximally similar to the scouring and deposition around submerged cuboids (Saunders, 2004). As a result, it is predicted that the relationships found through modelling relating the geometry and orientation of cuboids to flow conditions will be upheld by the wreck sites presented here. Predictions can be made as to the behaviour of the flow at each site and how this might shape the resultant scouring and accumulation around the wreck structure and ultimately, whether or not the site maintains the same quasi-stable state as the SS Richard Montgomery.

The Scylla might seem the obvious first choice based upon the similarities in wreck geometry to that of the Richard Montgomery (Table 4.3). Since both structures are near perpendicular to the prevailing flow this gives them both width to height (W:H) ratios in excess of 13 (Table 4.3). Structures with ratios over 6 and/or orientated more perpendicular to the flow generally promote a more 2D flow regime (predominantly flow over the object, resulting in a extended upstream and downstream reattachment length) (Dix et al., 2007). Furthermore, there are also many similarities between the two sites’ environmental conditions. Both sites have sediments composed largely of fine sands within the range of 0.125 - 0.2mm, with mean critical thresholds for transport of 0.16Nm$^{-2}$. Despite having such low threshold for transport under mean tidal currents, the threshold for transport is not met at either site. Though mean orbital velocities are sufficient for transport, the resultant mean combined wave and tidal flow at both sites is insufficient for transport. Whilst peak tidal velocities (not including for near-structure flow amplification) at the Scylla are still insufficient for sediment transport (unlike the Montgomery) under combined peak tidal and wave conditions both sites have sufficient bed shear stress to initiate sediment transport. Furthermore, both sites are situated on morphologically stable patches of seafloor (a stable sandbank in the case of the Montgomery and a gently
sloping seabed in the case of the Scylla). Where the two sites differ is in: i) the depth of surficial sediments (the Scylla only has 10’s centimetres of unconsolidated sediment atop bedrock, whereas the Montgomery has at least 12m of unconsolidated sediment which can be scoured), ii) the strength of the tidal asymmetry at the site (the Scylla has a residual almost twice that of the Richard Montgomery, as a result of this directional dominance deeper scouring could potentially be attained; Melling, 2014) and iii) the age of site (the Scylla wrecked in 2004 whereas the Montgomery wrecked in 1944). This final difference can be overcome since a single beam survey was taken of the Montgomery in 1952, just 8 years after sinking, as a result a comparison can be made between the initial 8 years of taphonomic processes at the two sites. Whilst initial scouring processes at submerged structures are expected to occur at an accelerated rate (Melling, 2014), the relatively quiescent environment and the potentially scour limiting geology of the region could counter this at the site of the Scylla.

Since the wrecks of the Burgzand Noord site have remained on the seafloor for over 300 years their superstructure is far less upstanding and ‘bluff’ in comparison with the Scylla and Richard Montgomery. As a result lower shear stresses and reduced spatial extent of scouring can be expected at this collection of wrecks (Roulund et al., 2005). Despite their low profiles (on average the wrecks stand just 1.5m proud of the seabed) the elongated wreck mounds of the Burgzand Noord wrecks have width to height ratios in excess of 20. In this respect, they are predicted to behave in a hydrodynamically similar way to that of the Scylla and Richard Montgomery. The fine sand composition of the bed at the Burgzand Noord site also makes this site relatively comparable to the Richard Montgomery and Scylla. Up until recently (circa. 1980) the wrecks of the Burgzand Noord site were completely buried. The completion of two dykes in the 1930’s dramatically altered the Wadden Sea basin in which the wrecks are situated. Increasing the tidal range by 0.5m over an 8 year period. As a result the bank under which the wrecks had remained buried for in excess of 300 years shifted. Therefore, the wreck sites have moved from one system state (buried) to another (exposed). If these wreck sites act as process-response systems, as described in Chapter 1 Section 1.2.4, then this recent shift is likely to have destabilised the system. Following this there are then two possible pathways: i) to re-stabilise at a new equilibrium level or ii) disequilibrium. This site gives the unique opportunity to observe a wreck site following a disturbance, an assessment of the resultant pathway will be made through the comparison of MBES surveys at this site, which should illuminate the present stability or instability of the site.

Whilst the catalyst for the perturbation at the Burgzand Noord site is anthropogenic the same two pathways (re-stabilisation or disequilibrium) are feasible at the site of the Stirling Castle, which, like the Burgzand Noord wrecks, spent the majority of its time buried (around 200 years) and only recently (first observed in 1979) became exposed once again as a result of large (multi-kilometre scale) sandbank migration within the Goodwin Sands system. Again, the present stability of this recently perturbed site will be assessed. Like
the Burgzand Noord wrecks, the *Stirling Castle* is exposed to a strongly asymmetrical tidal current. Despite the coarser sediment material at this site (1.26mm in comparison to 0.063 - 0.15mm at the Burgzand Noord site) transport under mean tidal conditions alone come to within 0.05Nm$^{-2}$ of the threshold for motion. Much like the previously described three sites, the *Stirling Castle* lies near perpendicular to the prevailing flow and has a relatively high width to height ratio (approximately 16), as a result a near 2D flow is expected in the wake for the wreck structure (similar to the *Richard Montgomery*, *Scylla* and Burgzand Noord sites).

Finally, the MBES time-series of the wreck of the *Algerian* will be presented. At this site, much like the *Stirling Castle*, the deep waters (>20m) and coarse grain sediment ($\approx 1.26$mm) limit the action of waves from mobilising sediment and similarly, mean tidal shear stresses are on the cusp of those required for sediment transport. Aside from these few similarities the wreck site of the *Algerian* is ultimately quite unique in comparison to the other four wreck sites. The wreck structure is situated in an area of morphologically very stable seabed and the wreck structure is near perfectly aligned with the prevailing flow (i.e. it has a very small angle of attack) giving the wreck a minimal width to height ratio (less than 2). As a result 3D flows are expected to prevail at this site and the resultant scour is predicted to be focused around the downstream end of the wreck (*Saunders, 2004*) or may be entirely absent (*Dix et al.*, 2007). The *Algerian* time-series offers the opportunity to observe the taphonomic processes at at wreck site with minimal or no scouring. This will allow for the assessment of the importance of the scour pit at the site of the SS *Richard Montgomery* to its stability.

In this section is has been shown that the case studies to be presented in this chapter share both a number of similarities with the previously introduced time-series of the *Richard Montgomery*, yet also, more importantly, differ in many of their hydrodynamic, geological and geometric attributes. Following this account of the similarities and contrasts between the sites the next four sections shall introduce the case study time-series one-by-one, empathising the impact of the differing environmental conditions on the wreck site’s taphonomy.

### 4.2 Scylla

In this section a MBES time-series composed of four repeat surveys spanning eleven years of the artificial reef wreck of the *Scylla* (monument number 1526504), located in Whit-sand Bay, Plymouth (Figure 4.2), are presented.
Chapter 4 Multibeam bathymetry time-series

Figure 4.2: a) Location of the wreck of the *Scylla*, depths relative to chart datum, b) bathymetry is from the 2013 Royal Navy survey, i) marks the location of the wreck of the *Scylla* and ii) the wreck of the *Eagan Layne*, c) bathymetry from the 2013 survey.
Figure 4.3: Photo of the scuttling of the HMS Scylla (ITV News, 2014).

Figure 4.4: Image of the pre-installation MBES survey and outlines of potential sites for installation of the Scylla. (Camidge and Holt, 2004).
4.2.1 Site description

The HMS Scylla, a 113m long, 13m wide, 2500 tonne Leander class frigate and was constructed in Plymouth in 1967 (Leece, 2006).

After suffering handling issues she was decommissioned in 1993 (Colledge and Warlow, 2010). In 2003 she was purchased by the National Marine Aquarium (NMA) with the intention to scuttle her, creating a diving attraction and to provide a habitat to marine life. The ship was stripped and treated to comply with Department for Environment, Food & Rural Affairs (DEFRA) specifications.

Whilst a pre-installation MBES survey was conducted by the Royal Naval Hydrographic School this survey was not available for this study. However, an image of the Digital Elevation Model (DEM) of this survey was obtained (Figure 4.4) and demonstrates that the chosen site was remarkably flat and featureless.

The ship was scuttled on the 27th March 2004 (Figure 4.3), becoming the UK’s first artificial shipwreck reef. Positioned at 050°19.665N 004°15.162W, she sits 500m north-west of the Liberty Ship the SS James Eagan Layne, sunk in 1945 (Figure 4.2ii). The ship’s bow was positioned to face towards the prevailing wind and wave direction, towards the south-west (236°). The wreck lies on a gentle slope (approximately 0.5°) with a depth of −21.2m CD at her bow and −19.9m at her stern and lists 10° towards her starboard side.

4.2.1.1 Geology

Grab samples were taken in the vicinity of the wreck by the NMA in 2004. Of these samples 14-19% was silt/clay (<0.0039 - 0.0625mm) with remainder predominantly (on average 65%) being medium to fine sand (0.0625-0.5mm).

In 1950 two cores were taken close to the Eagan Layne, one positioned 91m to the west of the wreck and another 91m to the north-west of the wreck (Holme, 1953). These had just 1cm and 18cm of loose sediment (again, composed of fine sands, 0.125 - 0.2mm) atop a layer of Devonian slate. Whilst the Eagan Layne is just over 500m east-south-east of the Scylla (so slightly closer into land than the Scylla), even those cores taken 2km off Rame Head had surface sediment depths of just 10.4cm. Therefore, at the Scylla wreck site sediment thickness is likely to be in the region of decimetres. This is confirmed by the presence of outcropping bedrock visible within the MBES data.

4.2.1.2 Tidal currents

The Scylla is exposed to a macrotidal regime, with a 4.5m spring and a 2.2m neap tidal range.
As part of a programme to monitor the impacts of dredged material disposal at the Rame Head site, approximately 1.5km south of the *Scylla*, a current meter was deployed on the wreck for five months (July - December, 2005). These data indicated that current flow is predominantly parallel to the coast, running towards the south-east during the ebb tide and towards the north-west during the flood, with the strongest flow on the ebb tide (Snelling, 2006). During summer months (25th July - 2nd September 2005), when the impact from wave driven currents was minimal, the current peaked during the ebb tide (135°) at 0.45m/s and was on average 0.17m/s (Figure 4.5). Whilst, during the flood tide currents peaked at 0.26m/s and was on average 0.12m/s.

![Figure 4.5: Mean current speed and direction from the 25th July 2005 to 2nd September 2005 derived from ADCP measurements (Snelling, 2006).](image)

### 4.2.1.3 Wave climate

Table 4.4: Storm return periods for Looe Bay. Data provided by the Channel Coastal Observatory (CCO).

<table>
<thead>
<tr>
<th>Return period (years)</th>
<th>Significant wave height (m)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.6</td>
<td>Depth-limited at MLWS</td>
</tr>
<tr>
<td>2</td>
<td>6.1</td>
<td>Depth-limited at MHWS</td>
</tr>
<tr>
<td>5</td>
<td>6.7</td>
<td>Depth-limited at HAT</td>
</tr>
<tr>
<td>10</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>8.3</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 4 Multibeam bathymetry time-series

Figure 4.6: Wave rose for Looe Bay wave buoy (water depth 10m CD) for the period of 2009 to 2012.

Figure 4.7: Time-series of significant wave height for Looe Bay wave buoy for the period of 2009 to 2014. The black line indicates the significant wave height of a 1 in 2 year storm and the red line, a 1 in 1 year storm.
Data from the Looe Bay wave-rider buoy are used to describe the wave climate at the site for the period of 2009 to 2015. This buoy is positioned just 10km south-west of the wreck site. Almost all waves approach from the south-west with a nearly insignificant proportion approaching from the south-east (Figure 4.6). It has been proposed that waves approaching from the south-west drive an alongshore transport of sediments in a south-easterly direction, perpendicular to the coastline (Vincent and Osborne, 1993).

During the survey period (excluding 2004 to 2009 since no data were available for this period) the largest storm occurred during 2012, generating significant wave heights of 4.54m (Figure 4.7). More recently, at the beginning of 2014, significant wave heights reached 7.32m at the site (equivalent to a greater than 1 in 10 year storm Table 4.4). This particularly stormy season may have skewed the return-periods towards higher values; since, for the rest of the observational period (2009 to 2013) not a single storm over the 1 in 1 year threshold is observed.

4.2.1.4 Storm record

Tide gauge elevation data are used from the Devonport tide gauge (located 7km north-east of the wreck site) to extend the storm record back to 1987 (Figure 4.8). From this record it can be seen that the first part of the observational period (from 2004 to 2011) was comparatively stormy with 2 greater than 1 in 1 year storms and 2 greater than 1 in 5 year storms. As a result, on top of the initial scouring rate (already expected to be rapid; Whitehouse, 1998), if storm induced motion can penetrate to the seafloor we would expect to observe an even more rapid rate of scouring due to wave induced sediment transport. Not a single 1 in 1 year or greater storm is observed over the rest of the time period (2011 to 2013) in close agreement with the wave record for this period of time.

As both records captured the peak in storm activity in 2013/2014 we can compare the return periods given for these events from both records. The wave record gave a peak return period of 10 years, whereas, the tide gauge record gave a peak return period of 7.8 years. Interestingly though, the 2012/2013 storms gave a wave return period well below the 1 year threshold, whereas, the tide gauge record gave a value of 6.2 years for the same storm. If we consider the tide gauge record to provide a better estimate of return periods out of the two records, since it covers a much longer period of time, it seems that the return periods for the wave record underestimate the significant waveheight of the high frequency (e.g. 1 in 1 year storms) and over estimates the height of the low frequency (e.g. 1 in 10 year storms).
Figure 4.8: Storm surge record from 1987 to 2015 for Devonport tide gauge. Greyed out periods of time indicate where no data were available. Both return period and frequency of storms (spacing of bars) shown.

4.2.1.5 Sediment transport potential

For a median grain size of 0.16mm (half way between the upper and lower bounds of the fine sand class, the predominant class at the wreck site) the critical threshold for transport is 0.16Nm$^{-2}$.

For a spring tide ebb current a maximum near-seabed (5m above bed) velocity of 0.45m/s can be expected, giving a depth averaged velocity in the region of 0.46m/s and in turn generating bed shear-stresses of 0.11Nm$^{-2}$; insufficient alone to drive sediment transport. As a result sediment transport is not predicted to occur at the site without the assistance from wave-induced bed shear stress or through local amplification of shear stresses around the wreck structure itself.

Based on a critical threshold for transport of 0.16Nm$^{-2}$ and using the significant wave height and return period from the Looe Bay 2009 to 2014 time-series, wave action alone is sufficient to induce transport at the site for 66% of the time. During the 2013/2014 storm wave-induced shear-stress peaked at 2.86Nm$^{-2}$. When considering a shear-stress amplification factor in the region of 3 to 4 around the structure then wave induced shear-stresses are sufficient for transport 91 - 94% of the time, respectively.

Clearly, at the Scylla wreck site, wave induced sediment transport will be predominant over tidally induced transport. As waves approach from the south-west (210°) the angle of attack of the waves is 26°. From this angle of attack the wreck has a cross flow width
of just 13m, giving a W:H of 1.5. At such a low W:H the structure is predicted to behave similarly to a pile or cuboid-like structure. Sumer et al. (1992) observed that under oscillatory flow a horseshoe vortex would form once the wave boundary layer was of sufficient thickness. A threshold was found for this formation at a value of the Keulegan-Carpenter (KC) number equal to 6, where KC is found using Equation 4.1, in which $U_W$ and $T_W$ are the amplitude of the bottom orbital velocity and associated period and $D$ is the diameter of the structure (in this case equal to the cross flow width).

\[
KC = \frac{U_W T_W}{D}
\]  

(4.1)

From the Looe Bay wave buoy series a peak (99.5% occurrence) $U_W$ of 1.1m/s is found, for which the $T_W$ is 12s. From this a peak KC of 1 is found for the Scylla. This is significantly below the requirement for horseshoe vortices to form. Taking $T_W$ to be fixed at 12s a $U_W$ in excess of 6.5m would be required for the KC value to exceed the threshold of 6. However, since the profile of the ship narrows towards the bow the value used for D (13m) is likely an over estimation. Thus, it is feasible that wave conditions could be sufficient to allow for the formation of a horseshoe vortex. The location of this vortex and associated trailing horseshoe vortices and eddy shedding are observed to be similar to the current alone scenario (Sumer et al., 1992). As a result, we can expect scouring around the bow of the ship to occur and potentially wake scour at the stern of the vessel (Dix et al., 2007).

### 4.2.2 Bathymetric data

The data presented here came from two different sources, the Royal Navy: 2004, 2011 and 2013 (June) and from a Plymouth University student (Elliot Gray): 2013 (March) (Table 4.5). Data were provided pre-gridded (with the exception of the 2013 March survey) and were given relative to CD and in WGS84/UTM zone 30N coordinates. DEM of Difference (DoD) analyses were carried out to the lowest gridded resolution (1m). The 2013 (March) survey covered the smallest area of seafloor (a 100m by 270m rectangle around the wreck) and the 2013 (June) survey covered the largest area, which also extended over the neighbouring wreck, the SS Eagan Layne.

Taking the average depth of the site to be 20m, sound speed to be 1482m/s (the depth averaged sound speed for the 2013 (March) survey), slope to be $0.5^\circ$, survey speed to be 1m/s (survey time 35 minutes, total survey length approximately 1.7km) the achievable along-track and across-track resolutions for each of the surveys are shown in Table 4.6. Despite the R2Sonic 2024 system having twice as many beams as the EM3000 Kongsberg the outer beam resolution for the R2Sonic system is twice as large due to the increased swath width. This highlights the very strong influence of the swath width on the resolution.
Table 4.5: Survey details for *Scylla* MBES surveys.

<table>
<thead>
<tr>
<th>Survey Year</th>
<th>Coverage (m²)</th>
<th>Sonar System</th>
<th>Positioning System</th>
<th>IMU System</th>
<th>Resolution (m)</th>
<th>Gray’s (2013) TPU (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 June</td>
<td>50,000</td>
<td>EM3000 Kongsberg</td>
<td>C and C technologies CNAV real time gypsy (RTG) system</td>
<td>Applanix POS MV version 4</td>
<td>1 ±0.12</td>
<td></td>
</tr>
<tr>
<td>2011 September</td>
<td>382,000</td>
<td>EM3000 Kongsberg</td>
<td>C and C technologies CNAV real time gypsy (RTG) system</td>
<td>Applanix POS MV version 4</td>
<td>0.5 ±0.12</td>
<td></td>
</tr>
<tr>
<td>2013 March</td>
<td>30,000</td>
<td>R2 Sonic 2024</td>
<td>Fugro Marinestar GPS</td>
<td>Applanix POS MV wave master</td>
<td>0.3 ±0.25</td>
<td></td>
</tr>
<tr>
<td>2013 June</td>
<td>390,000</td>
<td>Kongsberg EM2040c</td>
<td>C and C technologies CNAV real time gypsy (RTG) system</td>
<td>Applanix POS MV version 5</td>
<td>0.5 ±0.12</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6: Across-track and along-track resolution for *Scylla* MBES surveys.

<table>
<thead>
<tr>
<th>System</th>
<th>Beam Width (°)</th>
<th>Beam Number</th>
<th>Across Track Angle (°)</th>
<th>Along Track Angle (°)</th>
<th>Coarsest Across-track Resolution (m)</th>
<th>Coarsest Along-track Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM3000 Kongsberg</td>
<td>130</td>
<td>127</td>
<td>1.5</td>
<td>1.5</td>
<td>3.0</td>
<td>1.2</td>
</tr>
<tr>
<td>R2 Sonic 2024</td>
<td>160</td>
<td>256</td>
<td>0.5</td>
<td>1</td>
<td>6.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Some large vertical \((z)\) and horizontal \((x,y)\) offsets were observed between MBES surfaces during preliminary comparisons. As the seafloor is relatively flat and featureless and there are areas of exposed bedrock, it was relatively easy to constrain these offsets between surfaces. All surveys were matched to the 2013 (June) survey since this was the most recent and covered the largest area (including exposed bedrock outcrops). The values used to match the surfaces are given in Table 4.7. Somewhat surprisingly the largest offset was observed between the 2013 (March) and 2013 (June) surveys of 1.75m. This does not coincide with a miss-applied datum since CD is 3.22m below Ordnance Datum (OD) at Plymouth. As the offsets between the 2013 (June) survey and the other three surveys are minimal (at most 0.32m) it is most likely that the 2013 (March) survey had a fixed vertical error.

Table 4.7: Horizontal \((x,y)\) and vertical \((z)\) corrections made to Scylla MBES surveys. No horizontal correction was performed if the Root Mean Squared (RMS) associated with the correction was larger than the correction itself.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Vertical Correction (m)</th>
<th>Horizontal Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 June</td>
<td>−0.05</td>
<td>Affine transformation (5 control points, total RMS 0.6m)</td>
</tr>
<tr>
<td>2011 September</td>
<td>−0.32</td>
<td>None</td>
</tr>
<tr>
<td>2013 March</td>
<td>−1.75</td>
<td>None</td>
</tr>
<tr>
<td>2013 June</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

Estimates of the minimum level of detection threshold \((\text{LoD}_{\text{min}})\) were made through comparing the elevation differences between surveys for an area of seafloor outside of the area of influence of the shipwreck (Table 4.8, location shown in Figure 4.9). The \(\text{LoD}_{\text{min}}\) value ranges between \(\pm 0.13\)m and \(\pm 0.16\)m.

By comparison, Gray (2013) provided an estimate of the Total Propagated Uncertainty (TPU) of each survey from the a-priori values of the instruments used including the Differential GPS (DGPS), Inertial Measurement Unit (IMU), MBES, Sound velocity, dimension control (vessel configuration offsets) and DEM resolution. A maximum TPU of \(\pm 1.12\)m was reported for the 2004 survey, whilst the 2011 and 2013 surveys have reported TPUs of \(\pm 0.62\)m and \(\pm 0.55\)m, respectively. The inclusion of the DEM resolution as part of the TPU calculation is somewhat puzzling, since, increasing the survey footprint over an area of flat seafloor would not incur an increase in the TPU. Since the comparison between surveys is conducted here at the lowest resolution of all four surveys (1m) this DEM resolution component of the TPU will be excluded from this analysis. The resultant TPUs are given in Table 4.5. The estimated TPU is twice as high for the 2013 (March) than the other three surveys, this largely results from the estimation of DGPS uncertainty which was 0.15m for the 2013 (March) survey and 0.02m for the other three
surveys. The propagated $\text{LoD}_{\text{min}}$ found using these a-priori estimates of TPU are given in Table 4.8. Whilst the estimate for the $\text{LoD}_{\text{min}}$ is comparable for the 2004 to 2011 period the higher TPU associated with the 2013 (March) survey generates a $\text{LoD}_{\text{min}}$ for the 2011 to 2013 (March) and the 2013 (March) to 2013 (June) far in excess of the ambient bed-level change threshold. For the rest of this section the $\text{LoD}_{\text{min}}$ a threshold of $\pm 0.2\text{m}$ will be used as a trade-off between the slightly lower observed ambient uncertainty and the higher propagated a-priori uncertainty.

Table 4.8: Minimum level of detection threshold between MBES surveys at the wreck of the *Scylla* for ambient area and calculated using Elliot Gray’s a-priori TPU estimates.

<table>
<thead>
<tr>
<th>Surveys compared</th>
<th>Minimum level of detection threshold (m)</th>
<th>Gray’s (2013) propagated minimum level of detection threshold (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 (June) - 2011 (September)</td>
<td>$\pm 0.16$</td>
<td>$\pm 0.17$</td>
</tr>
<tr>
<td>2011 (September) - 2013 (March)</td>
<td>$\pm 0.13$</td>
<td>$\pm 0.28$</td>
</tr>
<tr>
<td>2013 (March) - 2013 (June)</td>
<td>$\pm 0.16$</td>
<td>$\pm 0.28$</td>
</tr>
</tbody>
</table>

4.2.3 Results

4.2.3.1 General site morphology

A description of the wreck morphology in terms of its height and width in relation to the prevailing flow at the site is provided in Table 4.9. The area of seabed (approximately 500m radius) surrounding the *Scylla* is remarkably flat and featureless with no visible bedforms near the wreck or further afield (Figure 4.9). This observation is in good agreement with the Meteorological and oceanographic (Metocean) and geological data which suggest that the wreck is situated in a location where prevailing conditions are insufficient to cause sediment transport (i.e. clear-water conditions).

An area of outcropping bedrock is visible 70m south-east of the wreck. This confirms the shallow sediment depths (at the very least in localised areas surrounding the wreck) as reported by Holme (1953) and is likely to retard the scouring extent at the wreck site, since bedrock (in this case Devonian slates) cannot undergo scouring.

The wreck structure itself is visible to differing degrees within each survey and is missing entirely from the 2011 survey (Figure 4.9b). Figure 4.10 shows the point cloud from the 2013 (March) survey shaded using the CloudCompare qPCV plugin. From these images it can be seen that the wreck forms a large bluff structure to any flow with no obvious
Figure 4.9: Depth surfaces for a) 2004 (June) b) 2011 (September) c) 2013 (March) and d) 2013 (June) survey. Depths relative to CD. DEMs are rotated by 45°. Location of ‘ambient’ area used in LoD_{min} calculation shown, along with the direction of the prevailing tide and wave environment.
Table 4.9: Wreck morphology of the *Scylla*.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth at wreck site, CD (m)</td>
<td>−19.9 - −21.2</td>
</tr>
<tr>
<td>Max. height above seabed (m)</td>
<td>14</td>
</tr>
<tr>
<td>Mean height above seabed, H (m)</td>
<td>8.5</td>
</tr>
<tr>
<td>Wreck beam (m)</td>
<td>13</td>
</tr>
<tr>
<td>Wreck length (m)</td>
<td>113</td>
</tr>
<tr>
<td>Across flow width, W (m)</td>
<td>13 (wave) 113 (tidal)</td>
</tr>
<tr>
<td>Orientation (°)</td>
<td>236/56</td>
</tr>
<tr>
<td>Angle of attack (°)</td>
<td>26 (wave) 79 (tidal)</td>
</tr>
<tr>
<td>W:H</td>
<td>1.5 (wave) 13 (tidal)</td>
</tr>
</tbody>
</table>

The height of the wreck is fairly constant from bow to stern with only a 4m elevation step. In Figure 4.10a a line can be seen which secures the wreck to the seafloor 50m south of the wreck. Since the wreck structure is sat almost upright on the seabed (the hull lists just 10° to the starboard; *PastScape, 2014*) and is relatively flat sided, the area of seabed not visible due to the obstruction of the wreck structure when surveying is minimal.

No scouring is observable within the 2004 (June) survey, the seafloor appears remarkably featureless. Whilst taken only three months after the wrecking event, extensive scouring has been observed to occur at tidally-dominant sites within a matter of just weeks (Melling, 2014). The *Scylla* is also subject to a strongly asymmetrical tidal current. Therefore, were tidal velocities sufficient for transport we would expect to observe a strongly asymmetrical scouring. This finding indicates that ambient tidal forces are insufficient to produce scouring at the site, congruent with the estimates of $\tau_c$ and $\tau_{cr}$ at the site (Section 4.1). Wave induced scouring is not predicted to have taken place during this period of time since the tide gauge record indicates no storms passed over the site. Furthermore, this observation indicates that the wreck likely didn’t make a significant depression in the seabed upon impact. Unlike the container ship, the *Hoegh Osaka*, which when it famously stranded on Bramble Bank (BBC News, 2015) created a crater, observable using MBES, with a maximum depth of 3.2m, 141m long and 10m wide, displacing approximately 975m$^3$ of sediment, forming two ridges either side of the pit. This could be a result of the depth of the site of the *Scylla* (20m in comparison to just 7.5m at the stranding site of the *Hoegh Osaka*), or the depth of the surface sediments (the thin veneer of sediment at the *Scylla* would prevent such a depression from forming) and also, potentially, the type of wrecking (the *Hoegh Osaka* was purposefully run into the bank, whereas, the *Scylla* was sunk in a controlled way to ensure it lay on its keel).
Figure 4.10: Point cloud from the 2013 (March) survey of the wreck of the *Scylla* proximally looking towards the a) north b) south c) west and d) east. Trihedron indicates up (blue), north (green) and east (red). No vertical exaggeration has been applied to the data. Ambient occlusion performed using qPCV plugin. Note the horizontal scale is different between a-b and c-d.

Within the 2011 survey (Figure 4.9b) and the subsequent two, 2013, surveys (Figure 4.9c-d) scouring is visible close to the wreck. An approximate outline of the scouring extent in shown in Figure 4.11a. Scouring is restricted to along the entire length of the starboard (western) side, around the bow (southern end) and at both towards the bow and, to a lesser extent, stern of the port (eastern) side. No scouring is observed around the stern and no areas of deposition are identifiable within the MBES. On average scouring extends 8m away from the wreck structure. Scouring has occurred down to a maximum depth of 1.2m (just off the bow on the starboard side) and to a maximum distance away from the structure of 20m (in a south-southwest direction away from the bow). This extension of the scour pit is aligned with the prevailing wave environment which is from the
south-southwest.

Figure 4.11: Schematic of scour and deposition around a) the *Scylla* (from 2011 onwards), extent informed by fill method given in Section 2.1.3.3, b) generalised scour around a submerged three-dimensional obstacle in unidirectional flow, after Dix *et al.* (2007), c) a breakwater under combined wave and unidirectional current, after Sutherland *et al.* (1999) and a short cylinder under oblique incidence waves displaying a d) initial scour pattern and d) expanded scour pattern (larger KC and Shields), after Voropayev *et al.* (2003).

In order to assess the predominant controls on the scouring observed at the *Scylla*, the results of four physical models of scour around submerged structures are presented in Figure 4.11. No studies could be found which looked at the impact of wave-aligned scour (most coastal structures are designed to dissipate wave energy), and so models tend to focus on structures perpendicular to the prevailing wave conditions, the similarities
of the scouring observed can be compared to unidirectionally flow aligned and wave-perpendicular flows. As indicated by Whitehouse (1998) the locations of the primary vortex, trailing horseshoe vortex and eddy shedding are similar to a current alone scenario. Therefore, the scouring at the Scylla should be analogous to the scouring to a flow aligned (unidirectional) structure.

The upstream local scour observed around the bow of the Scylla shares similarities with that observed from a unidirectional current alone (Figure 4.11b). In the case of the unidirectional flow, scouring results from the formation of a horseshoe vortex about the edge of the structure (Saunders, 2004). However, unlike this scenario, there is no evidence for downstream wake scour or any areas of associated deposition. Equally, areas of deposition were observed by Sutherland et al. (1999) (Figure 4.11c) when a model breakwater was exposed to both waves and unidirectional current. This model was run under ‘live bed’ conditions (ambient velocities away from the structure were sufficient for bedload transport), which could explain why areas of deposition are observed in these models but not around the Scylla. Unlike the observations’ of Dix et al. (2007) and Sutherland et al. (1999) observations, Voropayev et al. (2003) observed almost no upstream scouring of their short cylinder (Figure 4.11d-e). This scouring (a triple-scour signature parallel to peak flow) more closely resembled that of a obstacle aligned 90° to the flow undergoing 2D-flow (Saunders, 2004). Voropayev et al. (2003) did note the presence of vortices on the onshore side of the cylinder. However, these only resulted in the formation of ripples and not scour.

In summary, the upstream scouring present at the site of the Scylla is indicative of wave induced, 3D, scouring through the formation of horseshoe vortices. This scouring shares similarities with obstacles that are flow aligned (even when that flow is non-oscillatory e.g. Figure 4.11b). Horseshoe vortices are only predicted to form when the KC value is greater than 6 (Sumer et al., 1997). Whilst the estimated KC at the site not exceed this threshold, the pattern for scour around the wreck structure observed within the MBES data is characteristic of scouring induced through the presence of horseshoe vortices. Indicating that the results of these empirical studies are not wholly applicable to this site, potentially due to differences in obstacle geometry. The evolution of this scour is explored further in the following section.

4.2.3.2 Bed-level change

Whilst no bedforms are observed in the area surrounding the wreck, scouring is observed around the wreck structure. Therefore, through flow alteration and enhancement near the wreck structure, sediment transport have occurred. The driving conditions for this change will now be considered.
Figure 4.12: Bedlevel change at the Scylla for a) 2004 (June) to 2011 (September) b) 2011 (September) to 2013 (March) and c) 2013 (March) to 2013 (June). LoD_{min} given in Table 4.8. Locations of transect for Figure 4.13 and 4.14 shown.
Figure 4.13: Transects of de-trended elevation from south-west to north-east upstream (A-B) and downstream (C-D) of the Scylla.
Figure 4.14: Transects of de-trended elevation from north-west to south-east at the bow (E) and stern (F) of the *Scylla*.

From 2004 to 2011 34.3% of the survey area underwent detectable change (percentage area where the change is greater than the TPU given in Table 4.8) (Figure 4.12a). Of this 98.2% was erosion and 1.8% was deposition. On average the bed-level dropped by 0.3m, equating to 3,680 ± 2,090m$^3$ of sediment removed. Closer to the wreck scouring reduced the bed-level by as much as 1.2m. Scouring had already occurred to a depth deeper than thought possible based on core data, which suggested only the surface few 10’s of centimetres were made up of unconsolidated erodible material. Therefore, there must be a large amount of spatial variability in the depth of surface sediments. Enhanced levels of scouring (>1m) occurred at the starboard stern side (north-western edge) (Figure 4.13 transect A) and the port bow side (south-eastern edge) (Figure 4.13 transect C and Figure 4.14 transect E). It is quite likely that the majority of this scouring happened during the first Winter, since the site was exposed to a greater than 1 in 8 year storm on the 27th October 2004 (Figure 4.8). This storm was powerful enough to remove the three marker buoys at the site (*Plymouth Diving, 2015*) and is the largest storm surge on record at the Devonport site. Though likely, since no survey was taken at the beginning of 2005 it cannot be proven that all the scouring took place over this period of time.

Further away from the wreck, downstream in the ebb (south-east), the seabed was observed to lower on average by 0.3m (Figure 4.13, transect D, years 2011 onward). Whilst greater than the threshold for detection, this bed lowering has not generated a scour pit.
which can be distinguished within the bathymetry, making it distinctly different from the proximal region of scouring described above. However, the pattern of this extensive bed lowering is concurrent with a wreck at 90° to the prevailing flow (Quinn, 2006) and suggests that a small proportion of the sediment transport processes at this site could be due to tidally induced (ebb-predominant) shear stresses.

During this period of time (2004 to 2011) there is no evidence of re-deposition of scoured material within the system. The bathymetric surveys for this period of time are, however, limited to just 80m in the downstream direction (east of the wreck). Therefore, were the sediment deposited further downstream this would not have been captured by these surveys (Dix et al., 2007). As a result, were deposition to have occurred over this period of time, the 2004 to 2011 DoD would likely have captured it, i.e. during this period of time the system lost material; in this respect it could be described as being an open system at disequilibrium with its surrounds.

From 2011 (September) - 2013 (March) (Figure 4.12b) virtually no areas of the seafloor underwent detectable change. Equally, between the 2013 March and June surveys (Figure 4.12c) just 1.9% of the area underwent detectable change. Some localised and scattered areas of erosion are observed between the two 2013 surveys. However, the pattern (survey track aligned) and magnitude (>4m in places) of these changes are suggestive of errors within the survey (most likely the 2013 (June) survey, which has some visible data artefacts).

Taking an average scouring rate to be 0.3m over 7 years (0.04m/yr) (the rate for 2004 to 2011), bed-level change would be undetectable using the present system over just a two year duration (e.g. from 2011 to 2013), i.e. rate of sediment change from 2011 to 2013 could be equal to that of 2004 to 2013 and merely be undetectable due to the uncertainty of the surveys. Though, as noted before, it seems that storm-induced wave shear stresses are predominant at this site, since 2011 to 2013 was relatively quiescent in terms of storm/wave activity, little or no bed-level change is likely to have occurred over this period of time.

In summary, the wreck site was a open system at disequilibrium during some of (but most likely just the initial Winter) of the period from 2004 to 2011. From 2011 to 2013 the site is thought to have reached or been close to equilibrium conditions with minimal exchange of material, i.e. it was a near-closed system.

The impact of future storm events on the site is uncertain. However, the potential future scouring extent at the Scylla can be estimated by observing the present scour at the Eagan Layne wreck 500m south-east of the site, which as been in situ since 1945. This will be addressed in the following section.
4.2.4 Discussion

4.2.4.1 Comparison with the SS James Eagan Layne

A bathymetry and sidescan sonar survey of the wreck of the Eagan Layne are presented in Figure 4.15. Since the Scylla and the Eagan Layne are within 500m of one-another the environmental conditions of the two sites are near identical. Fortunately, both wrecks are also in the same alignment and so the angle of attack of the tidal and wave shear stress is the same. The only large difference between the two sites is their age. The Eagan Layne has been on the seafloor since 1945, whilst the Scylla was only sunk in 2004. Whilst no MBES time-series could be accessed for the Eagan Layne, it is included here as an end member to the taphonomic pathway which the Scylla will likely follow.

Scouring around Eagan Layne, both observed within the sidescan data (a dark halo surrounding the wreck delineates the distribution of finer sediment found within the scour pit) and the MBES survey, is restricted to within 26m of the structure (in comparison to 20m at the Scylla). The shape and extent of the scouring is similar between the two surveys and suggests that the sediment composition has not been altered outside of the scour pit. At its deepest scour has occurred down to a depth of 1m relative to the ambient bedlevel (in comparison to 1.2m at the Scylla). The deepest areas of scour are primarily restricted to the south-western (stern) end of the wreck. A very weak spatial asymmetry exists between the scouring along the port and starboard side of the wreck, with just a 2-3 metres more scouring along the north-western (port) side. Tidal currents are stronger towards the south-east (ebb) direction. Therefore, the reduced extent of scouring along the south-eastern side of the wreck further indicates that tidal transport is not predominant at this site.

Both spatial extents are very similar between the Scylla (from the 2011 survey onwards) and the Eagan Layne (both have maximum scour depths of \(\approx 1\)m and on average scouring extends 8m away from the Scylla and 10m away from the Eagan Layne). Therefore, it is probable that the Scylla has already reached a near-equilibrium state with its surrounds. To address the driving forces behind this limited scouring in this environment a comparison is now made with the site of the SS Richard Montgomery.

4.2.4.2 Comparison with the SS Richard Montgomery

Within 8 years of wrecking the Sheerness Middle sandbank, on which the Richard Montgomery is situated, had been scoured down to a depth of 7m. The associated scour pit extended more than 150m to the west of the wreck and 50m to the east. This scouring represented about 58% of the extent which is observed presently at the site. In other words, the wreck site was not yet at equilibrium. By comparison, the seabed surrounding the Scylla, over the first 7 years, scoured by a maximum of just 1m and extended
Figure 4.15: a) Sidescan sonar survey of the *Eagan Layne* conducted by ProMare as part of the Liberty 70 Project (http://www.promare.co.uk/liberty70) in April 2010 b) 2013 MBES DEM of the *Eagan Layne* and for comparison, c) MBES DEM of the 2012 *Richard Montgomery* survey, at the same scale. Clear steps observed within the *Eagan Layne* bathymetry are data artefacts.

only 13m away from the starboard side and 10m from the port side (excluding the near-undetectable scouring). However, by comparing this to the wreck of the *Eagan Layne*, it is proposed that this already represents a near end-member state. From this it can be deduced that the wreck of the *Scylla* more quickly reached its near-equilibrium state than the SS *Richard Montgomery*. However, an important factor to take into consideration is the acceleration of scour at the site of the *Scylla* due to the occurrence of a 1 in 8 year storm during its first winter *in situ*. Had the site not been exposed to such a storm so early on then perhaps the wreck may have taken longer to reach its present state.

The parallels between the wreck of the *Eagan Layne* and the *Richard Montgomery* are clear to see. Both World War II (WWII) Liberty ships, both sunk within a year of one another, and settled on a a surface of fine sand. Even the masts of the *Eagan Layne*,
much like the Richard Montgomery to date, were initially visible above seallevel. Despite this, the scour spatial extent and depth at the Eagan Layne is vastly reduced in comparison to the Richard Montgomery. There are two possible drivers of the limited scour at the Eagan Layne site: i) the depth of the surficial sediment prevents further scouring and/or ii) the minimal (below critical threshold) tidal current strength. Without sediment core data directly from the site it is difficult to differentiate which of these two drivers is more influential on limiting the scouring observed at the site. Based upon the observations of Sutherland et al. (1999) wave induced scour alone would be able to generate maximum scour depths of around 1m for a obstacle the size of the Eagan Layne or Scylla. Therefore, there is no apparent strong contribution from tidal scouring at either of the two sites.

4.3 Burgzand Noord

In this section two time-series are presented: one time-series composed of 6 repeat surveys spanning 5 years of the Burgzand Noord wreck site (a collection of 5 wrecks are captured within this MBES time-series) located in the Wadden Sea (Figure 4.16) and a further time-series which extends upon the first time-series but exclusively over the BZN 11 wreck (made up of 10, higher-resolution, surveys over a 7 year time period). This collection of wreck sites provides the unique opportunity to study the impacts of differing wreck geometry (including the alteration of this through differing management techniques) on a site’s taphonomic pathway whilst fixing all other site properties (geology, hydrodynamics, geomorphology etc).

4.3.1 Site description

The Burgzand Noord wreck site lies on the south-eastern edge of the Texelstroom Channel, in the Wadden Sea, 4km off Texel Island (Figure 4.16). At its shallowest the site is −5m (relative to Normal Amsterdam Level; NAP) and slopes down towards the north-west where it reaches a maximum depth of −10m.

4.3.1.1 Archaeological context

The Burgzand Noord wrecks are a collection of 17thC vessels, mostly either armed traders or India-men. The characteristics of each wreck are described in Table 4.10. This aggregation of wrecks formed at the Texel Roads as this area was a popular anchorage point for vessels seeking a safe location for the trading of goods and to await the right winds to sail to the markets of Amsterdam. Eight wrecks lie within the bathymetric survey area for 2002 to 2007 (BZN 3, BZN 4, BZN 8, BZN 9, BZN 10, BZN 11, BZN 17 and BZN
Figure 4.16: Location map of wrecks of the Burgzand Noord site in the Wadden Sea. a) and b) use bathymetry from Rijkswaterstaat (2001). Includes surveys from 1997 - 1999. c) bathymetry surface from the 2007 survey of the Burgzand Noord site with location of wrecks.
Table 4.10: Name and description of each Burgzand Noord wrecks’ captured within the 2002 - 2007 time-series. Extracted from van den Brenk et al. (2014)

<table>
<thead>
<tr>
<th>BZN</th>
<th>Found name</th>
<th>Working name</th>
<th>Date</th>
<th>Management history</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1985</td>
<td>Water barrels wreck</td>
<td>1775</td>
<td>Partially covered with netting (since 2001?)</td>
</tr>
<tr>
<td>8</td>
<td>1997</td>
<td>The Lily</td>
<td>1660</td>
<td>Covered with netting in 2003.</td>
</tr>
<tr>
<td>10</td>
<td>1999</td>
<td>Lily 2</td>
<td>1700</td>
<td>Partially covered with netting in 2000, extended in 2001 to 800m² and in 2003 to 2000m². South-eastern corner covered with artificial seagrass frond mats in 2012 (outside of the survey period).</td>
</tr>
<tr>
<td>11</td>
<td>1997</td>
<td>Big Empty</td>
<td>1650</td>
<td>Decided not to physically protect end to monitor degradation. A 11m long fragment of stern was excavated in 2001.</td>
</tr>
</tbody>
</table>

18). Five wrecks (BZN 3, BZN 4, BZN 8, BZN 10 and BZN 11) are described within this section as there are at least two surveys covering each of these wrecks.

All of these wrecks, with the exception of BZN 11, have had protective, polypropylene, netting placed over them to encourage deposition and reburial of the site. Some of this netting has been replaced and extended over the observational period (details given in Table 4.10). The effectiveness of these methods will be assessed by observing the rate and extent of deposition immediately following the implementation e.g. at BZN 3, 8 and 10 for the period of 2003 - 2004.

At the time of discovery the BZN 11 wreck had already spent a significant amount of time exposed and was undergoing serious deterioration. It was deliberately decided to let the remains of the BZN 11 lie unprotected in order to monitor the consequences. The BZN 11 has, therefore, been selected for further study, as it represents an unaltered system and original point density files for 2006 - 2014 are examined within this section.

4.3.1.2 Geology

The Texelstroom Channel has a bottom composition which is largely loose sand, atop erosion resistant layers of Pleistocene clay/silt and peat (Elias et al., 2006). The surface Holocene layers (Naaldwijk Formation) are made up of fine sands (63 - 150µm) (Figure 4.17). At 7m below this layer is a more clay rich, erosive resistant, Pleisotocene layer (-15m Normal Amsterdam Level; NAP).
4.3.1.3 Geomorphology

Since the construction of the dyke at Balgzand in 1924 and the Afsluitdijk Dyke in 1932 the Wadden Sea basin has undergone a major reconfiguration. The severing of the tidal channels that connected the Wadden Sea to the Zuiderzee (now the IJsselmeer) has led to the southward migration of the Texelstroom Channel (by a total of approximately 500m adjacent to the Burgzand Noord site) and the southern-eastern migration (by approximately 500m) and deepening (>5m) of the Scheer Gulley (van den Brenk et al., 2014) (locations of features shown in Figure 4.16). The migration of the Scheer Gulley is still observed from 1986 to 1991 (Figure 4.18a) and from 1991 to 1997 (4.18b). The wrecks were observed to be exposed to the surface in the mid 1980s (Manders et al., 2014). From 1986 to 1991 an average change within the survey zone (marked by a black outline in Figure 4.18) of $-0.55m$ (0.11m loss per year) was observed. From 1991 to 1997, over the same area, a further 0.31m of bed-level was lost (0.05m loss per year). These two snapshots suggest a deceleration in the rate at which the bed-level is dropping year-on-year. This is in agreement with tidal range values which although increased by 0.5m from 1926 to 1933, from 1933 to 2003 this increase was just 0.1m, indicative of a stabilisation of the Texel Basin (Vroom et al., 2012). The Wadden Sea reconfiguration following the completion of the dyke structures in the 1930s is expected to continue until sometime around 2040 to 2060 (Vos, 2003). Whilst the migration of these tidal channel systems are presently leading to the exposure of the BZN wrecks, it is thought that the movement of these channels also led to the initial burial and preservation of these wrecks (Manders et al., 2014).
Figure 4.18: Bed-level change over the Texel Channel and Scheer Gulley from a) 1986 to 1991 and b) 1991 to 1997 overlain on a hillshade of the 1997 bathymetry. Bathymetry from (Rijkswaterstaat, 2001). Outline of Burgzand Noord site shown in black.
There are two further processes contributing towards the decrease in the bed-level elevation: i) due to natural gas extraction the Wadden sea basin has been subsiding at a rate of 3-6mm/year (van den Brenk et al., 2014) and ii) large scale geological processes (e.g. glacial rebound) also contribute to subsidence, at a much lower rate of approximately 0.2mm/year (van den Brenk et al., 2014). Bed-level change at the wreck site (observed through singlebeam bathymetry time-series) has been occurring at a rate 100 times greater than the background subsidence rate; from 1852 to 2005 the site deepened by 5.99m (a rate of 4cm/year) (van den Brenk et al., 2014).

### 4.3.1.4 Tidal currents

The area has an average tidal elevation range of 1.65m (Vroom, 2011). Spring flood tidal currents peak at a maximum of 1.3m/s, whereas ebb tides peak at just 1.2m/s (van den Brenk et al., 2014).

### 4.3.1.5 Wave climate

To the west of Texel Island, i.e. within the North Sea, wind speeds can reach in excess of 35m/s. These predominantly north-westerly winds are capable of setting-up waves with significant heights in excess of 6m. However, on average (80% of the time), waves have significant heights of less than 0.5m and do not exceed 2m. The presence of Texel Island shelters the Burgzand Noord site so successfully (the maximum possible fetch is just 27km) that the effect of wave forcing within the basin is minimal (van de Waal, 2007).

### 4.3.1.6 Sediment transport potential

Small highly asymmetrical sand ripples, of height 0.2 - 0.4m and wavelength 7 - 15m, suggest a net sediment transport towards the east-northeast, aligned with the prevailing flood tide and wave transport direction. This was confirmed in 2011 when during the annual survey of the site a patch of the seafloor was surveyed twice, once on the 10th November and again on the 15th November; over this 5 day period the sand megaripples had migrated eastward by 4m (0.8m a day) (van den Brenk et al., 2014). The prevalence of these bedforms across the site and the small variability in their properties (height, wavelength, shape) indicates that the hydrodynamic conditions at each of the wreck sites is similar. Consequently, observed differences at the sites (scour pit extent, temporal variability in bed features etc) will only result from differences in the wreck’s geometry and orientation.


4.3.2 Bathymetric data

All surveys were provided in x,y,z format. Only the later surveys for the BZN 11 area were provided ungridded (i.e. at the original point spacing). Processing of the data was carried out by PeriplusArcheomare. As all data were acquired using Real Time Kinematic (RTK)-Global Positioning System (GPS) no tidal corrections were necessary. Depths are given relative to NAP and no vertical or horizontal offsets were necessary. Details of each survey are given in Table 4.11.

Table 4.11: Survey details for the Burgzand Noord time-series.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Coverage</th>
<th>Gridded?</th>
<th>Transducer system</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 2002</td>
<td>BZN 10</td>
<td>Yes - 1m</td>
<td>Seabat 8101</td>
</tr>
<tr>
<td>July 2003</td>
<td>BZN 3, BZN 8, BZN 10, BZN 11</td>
<td>Yes - 0.5m</td>
<td>Seabat 8125</td>
</tr>
<tr>
<td>June 2004</td>
<td>BZN 3, BZN 8, BZN 10, BZN 11, BZN 17, BZN 18</td>
<td>Yes - 0.5m</td>
<td>Seabat 8101</td>
</tr>
<tr>
<td>June 2005</td>
<td>BZN 3, BZN 4, BZN 8, BZN 10, BZN 11, BZN 17, BZN 18</td>
<td>Yes - 0.5m</td>
<td>Seabat 8125</td>
</tr>
<tr>
<td>October 2006</td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125</td>
</tr>
<tr>
<td>October 2007</td>
<td>BZN 3, BZN 4, BZN 8, BZN 9, BZN 10, BZN 11, BZN 17, BZN 18</td>
<td>Yes - 0.5m</td>
<td>Seabat 8125 (slanted)</td>
</tr>
<tr>
<td></td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125 (slanted)</td>
</tr>
<tr>
<td>September 2008</td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125 (slanted)</td>
</tr>
<tr>
<td>April 2009</td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125 (slanted)</td>
</tr>
<tr>
<td>June 2010</td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125 (slanted)</td>
</tr>
<tr>
<td>November 2011</td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125 (slanted)</td>
</tr>
<tr>
<td>October 2012</td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125</td>
</tr>
<tr>
<td>July 2013</td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125</td>
</tr>
<tr>
<td>December 2013</td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125</td>
</tr>
<tr>
<td>2014</td>
<td>BZN 11</td>
<td>No</td>
<td>Seabat 8125</td>
</tr>
</tbody>
</table>

4.3.2.1 Resolution and object detection

Assuming the four following constants: 8.5m water depth (the average depth of the Burgzand Noord site), $-3$ to $3^\circ$ (average slope across site), speed over ground of 1.5m/s and sound
velocity of 1500m/s; then Table 4.12 gives the achievable beam footprint and beam spacing for the Seabat 8101 and Seabat 8125 systems.

Theoretically the Seabat 8101 system should be capable of resolving objects 17m by 17m at the outermost beams (when slope is away from the transducer), but could resolve objects 0.6m by 0.6m below the nadir. The Seabat 8125 should be capable of resolving objects 1.2m by 1.2m at the outermost beams (when slope is away from the transducer) and down to 0.18m by 0.18m at the nadir. However, the above calculations assume a 0% overlap between tracks. This is unlikely to be the case; as a result the point spacing is likely to be significantly more dense. This shall be tested, in the following sub-section, using MBES data with original point spacing (2006 - 2014).

4.3.2.2 BZN 11 time-series data

As shown in Table 2.9 a much longer time-series (13 surveys over 11 years) is available for BZN 11. The later surveys (2006 - 2014) have been provided at their original point spacing. Therefore, DoD analysis can be carried out at a slightly higher resolution for these years. Additionally, an estimation of the DEM error can be made through coincident point analysis. Mean distance between points was in the range of 0.035m (2014) to 0.095m (2009) (Table 4.13); a factor smaller than predicted using the survey specifications (Table 2.10).

The lowest sample resolution of any of the 2006 to 2014 BZN 11 surveys is of the 2009 survey which had a point spacing of 0.095m. Therefore, the DoD analysis is run at a resolution of 0.4m as a trade-off of information and computational burden and allowing for tools, such as TopCAT Roughness (described in Chapter 5), to be applied to the DEM.

As the distribution of the elevation differences between the coincident points was skewed (distributed more highly towards lower values) the log of the value was taken before the mean and 95% confidence interval were found. On average, for the 2006 to 2014 surveys, the elevation between coincident points is just 0.05m (Table 4.14). Whilst z error of coincident points peaked in 2009 the large standard deviation of this value suggests that the sample number is potentially insufficient to describe the z error. At the 95% confidence level the z error is on average within ±0.22m (and is just ±0.17m when the 2009 survey is excluded). A LoD\textsubscript{min} of ±0.2m will be used, as the precision of the threshold can only reasonably be resolved to one decimal place.

This LoD\textsubscript{min} corresponds well with the range of net, consecutive survey, bed-level change observed within the selected ambient area (since no areas of bedrock or other stationary objects were surveyed, an area of seafloor was selected upstream of the wreck sites to ensure minimal impact from flow alteration past the wrecks) of −0.2 - −0.07m (Figure 4.22a).
Table 4.12: Achievable MBES resolution for the Burgzand Noord surveys. Information acquired from van den Brenk et al. (2014).

<table>
<thead>
<tr>
<th>System</th>
<th>Angular sector (°)</th>
<th>Beamwidth when seafloor slopes towards (m)</th>
<th>Beamwidth when seafloor slopes away from MBES (m)</th>
<th>System (slanted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seabat 8101</td>
<td>150</td>
<td>0.19</td>
<td>0.06</td>
<td>Outermost</td>
</tr>
<tr>
<td>Seabat 8125</td>
<td>120</td>
<td>0.77</td>
<td>0.06</td>
<td>Across-track</td>
</tr>
<tr>
<td>Seabat 8125</td>
<td>120</td>
<td>0.06</td>
<td>0.06</td>
<td>Alongtrack</td>
</tr>
<tr>
<td>Seabat 8101</td>
<td>150</td>
<td>0.77</td>
<td>0.06</td>
<td>Nadir</td>
</tr>
<tr>
<td>Seabat 8125</td>
<td>120</td>
<td>0.06</td>
<td>0.06</td>
<td>Outermost</td>
</tr>
<tr>
<td>Seabat 8101</td>
<td>150</td>
<td>0.77</td>
<td>0.06</td>
<td>Across-track</td>
</tr>
<tr>
<td>Seabat 8125</td>
<td>120</td>
<td>0.06</td>
<td>0.06</td>
<td>Alongtrack</td>
</tr>
<tr>
<td>Seabat 8125</td>
<td>120</td>
<td>0.06</td>
<td>0.06</td>
<td>Nadir</td>
</tr>
<tr>
<td>Seabat 8101</td>
<td>150</td>
<td>0.77</td>
<td>0.06</td>
<td>Outermost</td>
</tr>
<tr>
<td>Seabat 8125</td>
<td>120</td>
<td>0.06</td>
<td>0.06</td>
<td>Across-track</td>
</tr>
<tr>
<td>Seabat 8125</td>
<td>120</td>
<td>0.06</td>
<td>0.06</td>
<td>Alongtrack</td>
</tr>
<tr>
<td>Seabat 8101</td>
<td>150</td>
<td>0.77</td>
<td>0.06</td>
<td>Nadir</td>
</tr>
</tbody>
</table>
Table 4.13: Average Nearest Neighbour point spacing for the BZN 11 surveys.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Mean point spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.058</td>
</tr>
<tr>
<td>2007</td>
<td>0.084</td>
</tr>
<tr>
<td>2008</td>
<td>0.076</td>
</tr>
<tr>
<td>2009</td>
<td>0.095</td>
</tr>
<tr>
<td>2010</td>
<td>0.060</td>
</tr>
<tr>
<td>2011</td>
<td>0.041</td>
</tr>
<tr>
<td>2012</td>
<td>0.070</td>
</tr>
<tr>
<td>2013 (July)</td>
<td>0.053</td>
</tr>
<tr>
<td>2013 (December)</td>
<td>0.055</td>
</tr>
<tr>
<td>2014</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Table 4.14: Z error of coincident points for the BZN 11 surveys.

<table>
<thead>
<tr>
<th>Year</th>
<th>No. coincident points</th>
<th>Mean difference between coincident points (m)</th>
<th>Standard deviation distance between coincident points (m)</th>
<th>95% coincidence range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>416</td>
<td>0.05</td>
<td>0.06</td>
<td>±0.20</td>
</tr>
<tr>
<td>2007</td>
<td>73</td>
<td>0.04</td>
<td>0.03</td>
<td>±0.10</td>
</tr>
<tr>
<td>2008</td>
<td>148</td>
<td>0.08</td>
<td>0.06</td>
<td>±0.19</td>
</tr>
<tr>
<td>2009</td>
<td>69</td>
<td>0.09</td>
<td>0.20</td>
<td>±0.67</td>
</tr>
<tr>
<td>2010</td>
<td>369</td>
<td>0.03</td>
<td>0.04</td>
<td>±0.11</td>
</tr>
<tr>
<td>2011</td>
<td>2394</td>
<td>0.04</td>
<td>0.08</td>
<td>±0.17</td>
</tr>
<tr>
<td>2012</td>
<td>180</td>
<td>0.03</td>
<td>0.10</td>
<td>±0.32</td>
</tr>
<tr>
<td>2013 07 18</td>
<td>1171</td>
<td>0.03</td>
<td>0.02</td>
<td>±0.08</td>
</tr>
<tr>
<td>2013 12 12</td>
<td>1137</td>
<td>0.02</td>
<td>0.03</td>
<td>±0.09</td>
</tr>
<tr>
<td>2014</td>
<td>13843</td>
<td>0.03</td>
<td>0.10</td>
<td>±0.29</td>
</tr>
</tbody>
</table>

4.3.3 Results

4.3.3.1 General site morphology

On the whole the wrecks of the Burgzand Noord site are relatively low in profile, this can be seen in Figure 4.19 which shows a point cloud of the BZN 11 wreck and an overlay of the wreck structure at this site. For all five wrecks the maximum wreck height above the seabed is 4.57m and on average just 1.53m (Table 4.15). Equally, average wreck mound slope is just 12.5°. The wrecks are relatively wide, with wreck length to beam ratios over the range of 1.1 to 1.75, excluding BZN 11, which has a length to beam ratio of 4.4 (Figure 4.20). The comparatively narrow structure of the BZN 11 wreck mound could be a
result of the wreck’s alignment; it has an angle of attack to the prevailing flow of just 36°, in comparison to the other four wrecks which have values in the range of 69 - 83°. The wrecks have relatively similar isoperimetric quotients (Q) (a quotient which relates the length of the perimeter which describes the area of the wreck to its area, where a value of 1 describes a perfect circle); indicating that they are all of similar irregularity in their morphology. BZN wrecks, with the exception of BZN 11, have width to height (W:H) ratios of greater than 20. Therefore, we expect to observe predominantly 2D flow at these sites. Structures with ratios over 6 (all BZN wreck sites, including BZN 11) generally promote a more 2D flow regime (predominantly flow over the object, resulting in a extended upstream and downstream reattachment length) (Dix et al., 2007). It has also been observed that changes in a structures orientation to the flow has a smaller impact on the key scour length scale when the W:H is greater than 10 (Lambkin et al., 2006). In other words, due to the high W:H ratios of these wreck sites the subtle differences in the alignment of the wreck structures should not dramatically alter the observed scour processes.

Table 4.15: Average wreck morphology for each wreck of the Burgzand Noord site. Values in brackets are actual ship dimensions from Brouwers (2009).

<table>
<thead>
<tr>
<th></th>
<th>BZN 3</th>
<th>BZN 4</th>
<th>BZN 8</th>
<th>BZN 10</th>
<th>BZN 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth at wreck site, NAP (m)</td>
<td>-8.5</td>
<td>-8.3</td>
<td>-8.4</td>
<td>-8.3</td>
<td>-9.0</td>
</tr>
<tr>
<td>Max. height above seabed (m)</td>
<td>4.6</td>
<td>3.1</td>
<td>2.5</td>
<td>3.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Mean height above seabed, H (m)</td>
<td>2.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Wreck beam (m)</td>
<td>35</td>
<td>25</td>
<td>20</td>
<td>32</td>
<td>7</td>
</tr>
<tr>
<td>Wreck length (m)</td>
<td>54 (35-40)</td>
<td>28</td>
<td>35</td>
<td>39 (35)</td>
<td>31</td>
</tr>
<tr>
<td>Across flow width, W (m)</td>
<td>57</td>
<td>36</td>
<td>37</td>
<td>39</td>
<td>13</td>
</tr>
<tr>
<td>Orientation (°)</td>
<td>159/339</td>
<td>153/333</td>
<td>167/347</td>
<td>161/341</td>
<td>228/48</td>
</tr>
<tr>
<td>Angle of attack (°)</td>
<td>75</td>
<td>69</td>
<td>83</td>
<td>77</td>
<td>36</td>
</tr>
<tr>
<td>Average slope over wreck (°)</td>
<td>11.8</td>
<td>12.8</td>
<td>10.9</td>
<td>13.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Isoperimetric Quotients (Q)</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>W:H</td>
<td>27</td>
<td>32</td>
<td>33</td>
<td>21</td>
<td>11</td>
</tr>
</tbody>
</table>

The extents of the scour pits and wreck mounds (shown in Figure 4.20) were informed using the fill tool described in 2.1.3.3. However, due to the presence of bedforms frequently the tool picked-out a large number of depressions around the wreck (Figure 4.21a). As a result a degree of subjectivity was required when using this tool to clean out the bedform depressions leaving only the areas of scour (Figure 4.21b). Conversely, the inverse method, used for picking out the wreck mounds and areas of deposition, did not always work (likely due to the wreck mounds being less well defined). As a result, for some of the wrecks the same contour is used for multiple years (e.g. BZN 10 for 2003 and 2004).
Figure 4.19: a) Point cloud of the 2006 survey of the BZN 11 wreck, with a times 2 vertical exaggeration, orientated towards the north. b) 2006 bathymetric surface of the BZN 11 wreck, overlain with site plan from 2000 investigation.
Chapter 4 Multibeam bathymetry time-series

Figure 4.20: Schematic of scour and deposition extents around each BZN wreck.

Figure 4.21: A comparison between a) all contours found using the fill tool method and b) contours cleaned to only show scour features, at the BZN 3 wreck for the 2007 survey.
The orientation and morphology of the erosional features associated with the presence of the Burgzand Noord wrecks are described in Table 4.16. Noticeably, all wrecks only have a single scour feature and no local scouring is observable (Figure 4.20). Studies have largely focused on the scour patterns when elongated structures are orientated at intervals of 67.5° and 90° to the flow (Lambkin et al., 2006); the angle at which the scour pattern shifts from a single scour to two scour pits is not well constrained. Therefore, the scour patterns at the BZN site suggest that even at angles of attack as steep as 83° a single scour is still formed.

As described previously the wrecks of the Burgzand Noord site have relatively low profiles and do not present themselves as large bluff obstacles to flow. Therefore, lower shear stresses and a reduced spatial extent of scour are expected at this collection of wrecks (Roulund et al., 2005). Since the maximum scour depth associated with any of the wrecks is just 2m, and unconsolidated surface Holocene layers are observed down to 7m, sediment depth is not a limiting factor on the scouring.

Table 4.16: Scour morphology for each wreck of the Burgzand Noord site.

<table>
<thead>
<tr>
<th></th>
<th>BZN 3</th>
<th>BZN 4</th>
<th>BZN 8</th>
<th>BZN 10</th>
<th>BZN 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scour pit area (m²)</td>
<td>76878</td>
<td>3575</td>
<td>1427</td>
<td>2276</td>
<td>3124</td>
</tr>
<tr>
<td>Scour orientation (°True)</td>
<td>69</td>
<td>61</td>
<td>63</td>
<td>81</td>
<td>84</td>
</tr>
<tr>
<td>Max scour length (m)</td>
<td>158</td>
<td>111</td>
<td>49</td>
<td>103</td>
<td>109</td>
</tr>
<tr>
<td>Max scour width (m)</td>
<td>65</td>
<td>59</td>
<td>51</td>
<td>42</td>
<td>56</td>
</tr>
<tr>
<td>Max scour depth (m)</td>
<td>2.0</td>
<td>1.2</td>
<td>0.6</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Average slope within scour pit (°)</td>
<td>5.86</td>
<td>6.98</td>
<td>5.84</td>
<td>5.78</td>
<td>5.35</td>
</tr>
</tbody>
</table>

On the whole the scour features are aligned east-northeast with the exception of BZN 10 and 11 which are aligned more towards the east, by 17° and 20°, respectively (Table 4.16). Average slope values vary by only 1.63° between sites and on average are 1.32° greater than the average ambient slope. The widest (65m), longest (158m) and deepest (2m) scour feature was associated with the BZN 3 wreck, which is also the longest and the tallest of the five wrecks.

Deposition is observed over large areas downstream of the wreck structures, predominantly to the south of the scour pit and also upstream at the BZN 3 site. This is in good agreement with the finding’s of Saunders (2004), where the scour pit emanates from the end of the structure orientated closer to the flow and the deposition emanates from the end further from the flow. Deposition in the updrift region of BZN 3 results from the obstruction posed by the wreck to ambient net sediment transport. By assuming that the accumulation extends from the top of the wreck and is composed of sand with an estimated stable slope angle of 2° (typical large sandwave stoss-side slope angle) then the
length scale can be estimated using trigonometry (i.e. \(H/\tan(2^\circ)\))(Dix et al., 2007). Utilising this assumption for BZN 3 gives an estimated accumulation distance of 60m, just 10m greater than the observed distance.

### 4.3.3.2 Bed-level change

For the purpose of this study when considering bed-level change around each wreck a rectangular extent is used, since the designation of the study extent when calculating the net (average between two consecutive surveys) bed-level change did not have a significant impact on the derived surface properties (a manually designated area resulted in a maximum ±0.02m difference in the mean values). The extents used for each wreck are shown in Figure 4.22.

For the periods of time from 2002 to 2003 and 2003 to 2004 within the ambient area, in terms of percentage coverage, 68.9% and 61.0% underwent erosion, respectively (Table 4.17 and Figure 4.22b-c). By comparison, for the periods of 2004 to 2005 and 2005 to 2007 the same area underwent 90.1% and 88.6% erosion, respectively (Figure 4.22d-e). Not only did the percentage area undergoing erosion increase over time, but the volume lost by erosion also dramatically increased, from 248.6m³ for 2002 to 2003, to 542.1m³ for 2003 to 2004 and then doubled once again from 2004 to 2005 at a volume of 1186.5m³. As the 2005 to 2007 result represents two years worth of change the annual erosional volumetric change for this period of time is 604.9m³, so comparatively similar to the period of 2003 to 2004. No wreck areas, nor the ambient area, underwent net (average over rectangular extent) accumulation between any two consecutive surveys.

In terms of percentage area for all years at BZN 3, BZN 4 and BZN 11 and for the years of 2004 to 2005 and 2005 to 2007 at BZN 8 and for all years except 2002 to 2003 at BZN 10, the wreck areas underwent less erosion than the ambient area. On average, deposition within the wreck areas accounted for on average 26% of the total area, in comparison to 21% of the ambient area. Whilst this might give the initial impression that wreck areas underwent less erosion, this may be a simplification of reality, since, in volumetric terms, for all years at BZN 3 and 11, for all year but 2003 to 2004 at BZN 10 and for 2003 to 2004 and 2004 to 2005 at BZN 8 the level of erosion was greater surrounding the wrecks than in the ambient area. Despite this, the volume of deposition was also greater at all wrecks for all years with the exception of BZN 8 for 2003 to 2003 and 2004 to 2005. In other words, wreck areas exhibited a much larger range of bed-level values, resulting from both strong erosion and deposition.

The range of bed-level change values observed within the ambient area stayed approximately constant between each survey (Figure 4.23), at most it was 2.48m (for 2002 to 2003) and at its smallest 1.53m (for 2005 to 2007). Whereas, for the area surrounding wreck BZN 3 the range of observed bed-level values at 5.13m for the period 2005 to 2007
Figure 4.22: Bed-level change at BZN 3, 4, 8, 10 and 11 for a) 2003 to 2007, b) 2002 to 2003, c) 2003 to 2004, d) 2004 to 2005 and e) 2005 to 2007 using minimum level of detection threshold of ±0.2m.
Table 4.17: Gross DoD budget results for each BZN wreck. Colour shading of cells indicates where values are greater than (red) or less than (blue) the ambient area for the same period of time.

<table>
<thead>
<tr>
<th>Area</th>
<th>Volumetric</th>
<th>Percentage coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Net Erosion m³</td>
<td>Erosion %</td>
</tr>
<tr>
<td>BZN 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004-2005</td>
<td>−3262.9</td>
<td>83.0</td>
</tr>
<tr>
<td>2005-2007</td>
<td>−5347.9</td>
<td>78.6</td>
</tr>
<tr>
<td>BZN 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005-2007</td>
<td>−10.6</td>
<td>53.9</td>
</tr>
<tr>
<td>BZN 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002-2003</td>
<td>−109.3</td>
<td>85.8</td>
</tr>
<tr>
<td>2003-2004</td>
<td>−405.5</td>
<td>64.4</td>
</tr>
<tr>
<td>2004-2005</td>
<td>−1240.2</td>
<td>89.5</td>
</tr>
<tr>
<td>2005-2007</td>
<td>−435.6</td>
<td>61.8</td>
</tr>
<tr>
<td>BZN 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002-2003</td>
<td>−306.5</td>
<td>69.5</td>
</tr>
<tr>
<td>2003-2004</td>
<td>−275.4</td>
<td>53.9</td>
</tr>
<tr>
<td>2004-2005</td>
<td>−2530.2</td>
<td>89.5</td>
</tr>
<tr>
<td>2005-2007</td>
<td>−1883.4</td>
<td>74.4</td>
</tr>
<tr>
<td>BZN 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003-2004</td>
<td>−323.2</td>
<td>57.6</td>
</tr>
<tr>
<td>2004-2005</td>
<td>−1177.3</td>
<td>80.9</td>
</tr>
<tr>
<td>2005-2007</td>
<td>−1768.7</td>
<td>88.6</td>
</tr>
<tr>
<td>Ambient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002-2003</td>
<td>−178.0</td>
<td>68.9</td>
</tr>
<tr>
<td>2003-2004</td>
<td>−293.6</td>
<td>61.0</td>
</tr>
<tr>
<td>2004-2005</td>
<td>−1141.8</td>
<td>90.1</td>
</tr>
<tr>
<td>2005-2007</td>
<td>−1167.9</td>
<td>88.6</td>
</tr>
</tbody>
</table>

(three times that of the ambient area for the same period of time) and was equally high for 2004 to 2005 at 4.59m.

Net bed-level changes were observed to be decreasing consistently from year to year, both in the zone influenced by the presence of the wrecks as well as in the ambient area. Values of net bed-level changes are in all but two cases more negative in regions influenced by the presence of a wreck (BZN 11 from 2003 to 2004 and BZN 4 from 2005 to 2007).

Transects of scour pits with time (Figure 4.24, locations of transects shown in Figure 4.20) indicate much of the change in bed-level is associated with the deepest part of the scour pit. The BZN 3 site shows the evolution from a shallow downstream slope in 2004 to a
Figure 4.23: Box-plot of change around each BZN wreck for a) 2002 to 2003 b) 2003 to 2004 c) 2004 to 2005 and d) 2005 to 2007. Study extents shown in Figure 4.22. Note, all wrecks (with the exception of BZN 11) have undergone some form of protection.
Figure 4.24: Transects through wreck and scour pit for 2002 - 2007 for a) BZN 3, b) BZN 4, C) BZN 8, d) BZN 10 and e) BZN 11. Transects from west to east.
much more defined pit in 2005 which then deepened further and migrated further downstream of the wreck in 2007. Another feature which is highlighted by the transects is the presence of a slight ridge to the scour pit downstream of the wreck sites (seen mostly clearly in Figure 4.24a, 2005 and d, 2007). This could possibly delineate the boundary between the areas of local (approximately 30 - 70m downstream of the wreck) and lee wake scouring.

Within the zones of influence, for those years where there is a large loss in bed-level, for example downstream of BZN 3 from 2005 to 2007 (where there the bed-level dropped by −2.8m), there was often a distinctly separated area of bed-level gain for the same period of time within the zone of influence, for example a gain of 1.9m was observed downstream of BZN 3 from 2005 to 2007. This suggests that as the rate of scouring increases so too does the deposition of material within the system. As with the Richard Montgomery, it is feasible that the material being deposited is the same as the material being excavated; indicating that material is reworked within the region of the wreck.

The maximum wreck height relative to the surrounding ambient bed is shown in Figure 4.25. Maximum wreck heights are greatest for BZN 3, BZN 4 and BZN 10. Furthermore, BZN 3 and 1 exhibit a far greater range of maximum wreck heights (0.72 and 0.55m, respectively) than the other three wrecks (ranges from 0.18 - 0.38m). The peak in maximum wreck height for both wrecks could result from increased deposition following reapplication of protective matting at the sites, which were extended at both sites in 2003 (Table 4.10). By raising the height of the wreck without altering the width of the structure the W:H ratio of the wreck is decreased. This is predicted to increase the mean and maximum total kinetic energy observed downstream of the structure, increasing the
local scouring and achievable maximum scouring depth (Dix et al., 2007). In agreement with this finding, it was observed that in terms of volume net bed-level change at the BZN 3 and BZN 10 sites was greater than twice the that of the ambient area and even 4.5 times as great for the BZN 3 wreck over the 2005 to 2007 period. Scouring was observed to increase the maximum scour depth at the two wreck sites from 2004 to 2007 by 1.6 and 0.6m, respectively (Figure 4.26).

![Figure 4.26: Maximum BZN scour depth relative to ambient bed for each survey.](image)

BZN 3 and BZN 10 share a very interesting pattern in their location of both their maximum wreck height and position of maximum scour depth (Figure 4.27). Both moved laterally relative to the wreck structure, giving the radius for spread of maximum scour depth for the two wrecks of 20 and 41m, respectively. This observation is in agreement with those of Saunders (2004) who observed that when a shipwreck underwent burial the scour pattern was always aligned with the dominant remaining upstanding section of the vessel. Although the positions do not always align, there may be a lag in the system, which is why there is still both a large spatial range of locations in both the location of the maximum wreck height and scour pit.

By contrast, BZN 8 was the only wreck whose maximum scour depth remained in a fixed position over the time-series (within a 3m radius) (Figure 4.27c). This is a somewhat surprising result as both the wreck height (Figure 4.25) and maximum scour depth (Figure 4.26) increased at this site over the same period. This, perhaps, highlights the relative importance of the location of the maximum wreck height, which for BZN 3 remained within a tight, 4m, radius.

The location of the maximum scour depth of the BZN 11 wreck remained relatively stable between 2003 to 2004 and 2005 to 2008, but made a 55m jump downstream between
2004 and 2005. No radical differences in wreck height, maximum wreck height location or scour depth are observed over this period, yet a huge regime change is observed in terms of the spatial patterning of scour at this site. Diver observations for this period reported a degradation of the south-eastern end of the stern and the loss of a fragment of ‘zaathout’ (inner plate) (Figure 4.19b, points 609 - 611). This could have modified the wreck structure in such a way as to have altered the flow over the wreck and the resultant scour. These alterations were not captured by the MBES time-series, perhaps indicating that the resolution used here was insufficient.

The spatial extent of the later surveys at the BZN 11 site (shown in Figure 4.28) is not sufficient to capture the whole scour pit. Certainty for the surveys of 12/12/2013 and 2014 the maximum scour depth is out of bounds (the observed maximum depth location within survey area is at the eastern-most bound). However, for the surveys of 2006, 2009, 2010, 2011 and 18/07/2013 the maximum scour depths are well within the bounds of the survey area and even, on several occasions (2009, 2010, 2012 and 2013/07/18), are observed upstream of the wreck structure. The bathymetry in these years suggests that there is no pronounced area of scouring associated with the wreck and as a result the
location of the maximum scour depth is dependent upon the location of the sand ripple troughs at the time of surveying.

The extended BZN 11 MBES time-series is now considered. The characteristics of the bed-level change observed from 2006 to 2014 will be tied-back into the 2002 to 2007 analysis.

From 2006 to 2007 (Figure 4.28a) a strong signal of bed-level gain is observed within the scour pit downstream of the BZN 11 wreck site, whilst, over the same period of time, a near equally strong level of elevation loss is observed over the wreck structure itself with a focus on the northern side of the central fragment (Figure 4.19b). From 2007 to 2008 (Figure 4.28b) this bed-level loss continues over the wreck and extends further to the east. Again, from 2008 to 2009 (Figure 4.28c) the elevation along the northern side of the wreck structure decreased, though, unlike in the previous year extensive bed-level gain is observed downstream (to the east) of the wreck structure. Between 2009 and 2010 (Figure 4.28d) bed-level loss atop the wreck was restricted to mostly the southern side of the structure with no detectable change downstream of the wreck (a trend which was maintained for all proceeding years). From 2010 to 2011 (Figure 4.28e) two small areas of bed-level gain were observed on the northern and southern side of the wreck. Whilst from 2011 to 2012, 2012 to July 2013, July 2013 to December 2013 and December 2013 to 2014 (Figure 4.28f-i) the wreck underwent near-zero change.

On a near decadal scale (2006 to 2014) (Figure 4.29) the magnitude of bed-level loss atop the wreck site observed for the years of 2006 to 2007, 2007 to 2008, 2008 to 2009 and 2009 to 2010 (Figure 4.28a-c) is made apparent. Up to 2m of material was removed from the wreck site over this period of time. Whilst from 2003 to 2007 the maximum wreck height at the site decreased, it was not nearly at the same rate observed from 2006 to 2014 (<0.1m/year for 2003 to 2007, in comparison with 0.25m/year for 2007 to 2014).

An equally strong signal (maximum of 1.68m over the 8 year period) of bed-level gain is observed to the east of the wreck within the scour pit, decreasing its maximum depth relative to the ambient bed from 1.4m in 2006 to 0.3m in 2014. In terms of volume change the wreck area (limits shown in Figure 4.29) lost a total of 113m$^3$ $\pm$ 32m$^3$ of material. Whilst the scour pit area (again limits shown in Figure 4.29) gained a total of 122m$^3$ $\pm$ 29m$^3$ of sediment, near perfectly balancing the loss of material observed of the same period of time.

In the latter half of the BZN 11 survey period (from 2008 onwards) the range of bed-level change values and the net bed-level change remain within the same bounds as the initial survey period (2003 to 2007) (Figure 4.30). Spatially the pattern of erosion of the wreck and deposition within the scour pit is the same over both periods. Resulting in an average total loss of 0.7m from the height of the wreck structure from 2003 to 2014.
Figure 4.28: Bedlevel change at BZN 11 for a) 2006 to 2007 b) 2007 to 2008 c) 2008 to 2009 d) 2009 to 2010 e) 2010 to 2011 f) 2011 to 2012 g) 2012 to July 2013 h) July 2013 to December 2013 and i) December 2013 to 2014 using minimum level of detection threshold of ±0.2m. Overlain on the more recent of the two year’s hillshade.
Figure 4.29: Bed level changed at BZN 11 for 2006 to 2014 using minimum level of detection threshold of ±0.2m. Overlaid on the 2014 hillshade. Outlines of the wreck and scour area used in zonal analysis are shown.

Figure 4.30: Box-plot of bed-level change around BZN 11. Note that the 2003, 2004 and 2005 surveys are at a lower resolution and so, some small scale changes may be lost.
Whilst for the periods of 2004 to 2005 and 2005 to 2007 for the rectangular area around the BZN used in Figure 4.23 the net bed-level change was more negative than the $\text{LoD}_{\text{min}}$ of ±0.2m. A more confined survey extent was only made available for the high resolution MBES surveys. As a result, when the periods of 2004 to 2005 and 2005 to 2007 are considered for this area (Figure 4.30) the net bed-level change is below the level of detection. In other words, cropping the study extent removed some of the scouring signal over these periods of time. Therefore, it is possible that with this latter time-series we are missing some of the scour and deposition processes occurring at this site.

4.3.4 Discussion

The Burgzand Noord site time-series has provided the very unique opportunity to study the impacts of differing wreck geometry (height, width, length, orientation and bluffness) on wreck site taphonomy whilst maintaining a fixed set of environmental conditions (tidal, wave and geological environments).

The singular scour feature to the north eastern side of the wreck structure present at all five BZN wreck sites is indicative of a strongly asymmetrical (in the flood tide direction) tidally dominated environment. The ubiquitous presence of asymmetrical bedforms across the site confirms this predominant mode of transport and indicates that ‘live’ scour is occurring at these wreck sites. The larger range in bed-level change observed downstream of the wrecks in comparison to the ambient area indicates that even though the wreck structures are not as bluff as other wrecks presented in this thesis (e.g. the Scylla and Richard Montgomery) the flow is still sufficiently amplified as to induce accelerated rates of erosion and deposition downstream of the wrecks.

Since the 1930’s the western part of the Wadden Sea basin has been undergoing sediment loss in response to the completion of the Afsluitdijk dyke, this is expected to continue until sometime around 2040 - 2060 (Vos, 2003, p.5). This regional sediment loss accounts for the negative year-on-year bed-level change in the ambient area (on average 0.1m between each survey). Downstream of the BZN wrecks net bed-level change was, in all but two cases, more negative in regions influenced by the presence of a wreck. Unlike the Richard Montgomery, the rate of erosion did not balance with the rate of deposition over an inter-annual time-scale. On average over the wrecks’ area of influence bed-level decreased by 0.3m between each survey. Therefore, in terms of the process-response system theory, these wrecks are presently open systems, undergoing material loss.

Despite BZN 3, 4, 8 and 10 being aligned between 69 and 83° to the prevailing flow, patterns of scour and deposition downstream of the wrecks more closely resembled that modelled for a elongated structure orientated 67.5° to the flow than 90° to the flow (i.e. only ever a single wake scour was observed) (Dix et al., 2007, p.104). BZN 8, despite having very similar wreck properties to BZN 4 (e.g. same height and a difference in W:H of just
1), has a much reduced region of scour both in depth (maximum scour depth 0.6m in comparison to 1.2m) and area (1427m$^2$ in comparison to 3575m$^2$). Downstream of the leading edge of the BZN 8 wreck towards the flow (where scour would usually emanate from) is a protrusion of the wreck structure. It is proposed that the presence of this feature has prevented the full development of a scour pit at this site.

In terms of their bed-level variability BZN 3 and BZN 10 stood out from the other three wrecks. Over the periods of 2004 to 2005 and 2005 to 2007 these wrecks displayed strong negative net bed-level change and large ranges in bed-level change values. There are two possible causes for this accelerated scouring at these wrecks: i) Both have significantly larger heights (2.1 and 1.8m, respectively) in comparison to the other three wrecks (which have heights equal to or less than 1.2m) and thus have lower W:H. Obstacles with lower W:H have been shown to produce higher values of total kinetic energy downstream and induce deeper scour pits than obstacles with higher W:H (Dix et al., 2007). ii) These two wrecks have a much larger variability in maximum wreck height across the time-series, possibly in response to the extension of the protective matting at these two sites in 2003 (Table 4.10). Changes in the height and thus W:H will have destabilised the system and induced new patterns in scour and deposition through shifting the reattachment length of the downstream vortex and altering the total kinetic energy of the flow. Whilst a lower W:H is associated with deeper scouring, the wreck of the BZN 11 has the lowest W:H of all the five wrecks. At this wreck the range in bed-level change values was consistently in the region of ±1m. This site has not undergone any physical protection unlike BZN 3 and BZN 10. Therefore, its geometry has more slowly altered with time, dampening any large changes in bed-level. This finding suggests that it is the change in the height of BZN 3 and BZN 10 which induced the increased range in bed-level change at these two sites and not their relative height. This finding has implications for the application of protective measures, since it suggests that whilst the height of the wreck is increased (through the deposition of material) this results in increased scouring downstream of the structure, which could potential uncover previously protected areas of wreck superstructure or loose artefacts. Therefore, when applying netting to a site it should be ensured that either downstream there are no areas of buried archaeological material, or the netting is extensive enough to cover these areas.

Year-on-year infilling of the scour pit associated with BZN 11 was observed, this can be attributed to the loss in height of the wreck structure, increasing the W:H ratio resulting in a decreased downstream flow amplification. Therefore, reducing the rate of scouring and even allowing for infilling of the original scour pit (Trembanis et al., 2007). In terms of sediment volume, the scour pit infilled over the period of 2006 to 2014 by the same amount that the wreck area lost. This maintenance of total sediment volume follows the trend observed at the wreck of the Richard Montgomery. Which is perhaps even more surprising in the case of the BZN 11 wreck since there is a strongly unidirectional sediment transport pathway, thus no obvious hydrodynamic forces working towards keeping
the eroded sediment within the wreck site system.

In summary, whilst the five wrecks of the Burgzand Noord site observed through the time-series presented here have sculpted collectively similar scour and depositional morphologies, their variability in bed-level change indicates a disparity in the year-on-year sedimentary processes occurring at each site.

### 4.4 Stirling Castle

In this section a multibeam bathymetry time-series composed of six repeat surveys spanning 7 years of the wreck of the *Stirling Castle* (National Monuments Record 1082115), located in the Goodwin Sands (Figure 4.31), is presented.

![Location map for Stirling Castle and Goodwin Sands bank features and location of metocean data recording sites. Overlain on 2009 Maritime and Coastguard Agency (MCA) contracted bathymetry of the Goodwin Sands bank.](image)

Figure 4.31: Location map for *Stirling Castle* and Goodwin Sands bank features and location of metocean data recording sites. Overlain on 2009 Maritime and Coastguard Agency (MCA) contracted bathymetry of the Goodwin Sands bank.

#### 4.4.1 Site description

The modern Goodwin Sands bank can be divided into several named areas (displayed in Figure 4.31). The bank is presently split into two main sections, the North Sand, or

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1 This section is based on work awaiting publication as Astley (in review, b).
Goodwin Knoll and the South Sand, or South Calliper; these two areas are separated by the Kellet Gut. The wreck of the *Stirling Castle* is located 13km offshore of the Kent coast (Figure 4.31), 15km from the town of Deal, in an unnamed flow dominant channel calved into the North Sand. Presently (based on 2009 multibeam data) the wreck sits at a depth of −15m CD (−17.9m Ordnance Datum; OD, using datum separation values taken from the Vertical Offshore Reference Frame; VORF). The Goodwin Sands is a complex sandbank system, incised by both flood and ebb tidal channels, the long term (decadal and greater) evolution of which is not fully understood (e.g. Cloet, 1954; Elderfield, 2001).

### 4.4.1.1 Archaeological context

The *Stirling Castle* was a third rate ship constructed in 1679 following the third Anglo-Dutch war. The vessel was approximately 45 metres long, with an original tonnage of 1059 and a crew 349 strong (Wessex Archaeology, 2003). The *Stirling Castle* was on her way back from a duty spent in the Mediterranean, in 1703, when she hit foul weather and set anchor in the Downs (a roadstead off the Kent coast). Winds were reported to be blowing from the south-west (Larn, 1977, p.55). Dragging on her anchor, her main-masts were cut down, but she finally sank on the 27th November 1703. Just 70 members of her crew were rescued. ‘The Great Storm’ of 1703 was responsible for a large number of wreckings, including the *Northumberland, Restoration* and the Royal Yacht *Mary*, leading to a total loss of lives of over 1,000 seamen within the Goodwin Sands region alone (Pascoe, 2012).

![Figure 4.32: Point cloud of the September 2005 survey of the *Stirling Castle*. Proximally viewed towards the north (Trihedron indicates up, blue; north, green; and east, red). No vertical exaggeration. Ambient occlusion performed using qPCV plugin.](image-url)
In 1979, when the wreck was first discovered by amateur divers, it was reported that the *Stirling Castle* survived to the level of its main deck (Perkins, 1979). At this point in time the wreck was remarkably well preserved; as evident by the wide range of organic (wooden, leather, silk and rope) artefacts found at the site (Whitewright, in review).

In 1980 the area of the seabed surrounding the wreck was designated under the Protection of Wrecks Act 1973. The wreck was largely buried from 1980 to 1998 (Whitewright, in review). Since 1979 the collapse of the main deck, gun deck and orlop deck has taken the structure down to a height of 4 - 5m relative to the surrounding seabed (Figure 4.32).

### 4.4.1.2 Geology

The Goodwin Sands, which formed during the Flandrian Transgression (D’Olier, 1981, p.222), consists of approximately 20 - 25 metres of unconsolidated, sandy sediments resting on an Upper Chalk platform (British Geological Survey, Thames Estuary Sheet 51°N-00°, 1:250 000 Series). The bottom types are fine sand with gravelly sand forming the base of the gully in which the *Stirling Castle* rests. Sediment samples from a 200m radius around the wreck were taken in 2006 (Bates *et al.*, 2007, p.81-2). Median grain size was found to vary across the site from 1794µm (very coarse sand) in the west and downstream of the wreck (within the scour pit), down to 263µm (medium sand) to the east of the wreck, with a mean grain size of 1265µm (Figure 4.33).

![Figure 4.33: Mean grain size at the *Stirling Castle* from 2005 analysis, overlain on April 2005 multibeam bathymetry.](image-url)
The only known sub-bottom profiler survey of the site was conducted in 1983 by Marine Archaeological Surveys (MAS) using an ORE subbottom profiler (Redknap, 1990). Redknap (1990) observed that at the Stirling Castle site the bedrock layer was 0.5m below the gulley bottom and was possibly scoured down to bedrock in places.

Dredging processes in the immediate vicinity of the wreck, within the North Sand Head zone, are thought to be likely to affect local sediment distribution (Wessex Archaeology, 2003, p.25). Five licenses were issued from 1976 and 1998 for the extraction of aggregate from the North Goodwin and South Goodwin areas, permitting over 9.5 million tonnes (6.3 million m$^3$) of material to be extracted (Natural England, 2012). Furthermore, a proposal has been submitted for the removal of an additional 2.5 million m$^3$ of aggregate from the South Goodwin area (Dover Harbour Board, 2015). Dover Harbour Board (2015) stated that this has the potential to both affect tidal current speeds and direction, and the wave climate, impacting upon patterns of erosion and deposition, which could potentially affect the stability of nearby morphological and archaeological features (including the Stirling Castle).

4.4.1.3 Geomorphology

Presently the Goodwin Sands bank spans approximately 24km in length and 10km in width and has a total area of approximately 220km$^2$ (using the 2009 −10m CD depth contour). At its deepest the bank reaches −40m CD, although the average depth of the chalk bedrock is around −20m CD (Carrizales, 2010, p.11) and at its shallowest the bank sits 1m above CD, i.e. it is surface piercing at certain states of the tide. Above the −20m depth surface the bank has a volume of approximately 1km$^3$ (estimated using 2009 MCA data).

The sinuous shape of the Goodwin Sands bank is consistent with a site of bedload convergence; a location where there is no net bedload transport (Kenyon and Cooper, 2005, p.22). Convergent-type sand banks are inherently unstable. Anecdotal evidence suggests the evolution of the Goodwin Sands follow a seven-year pendulum swing from east to west and back again (Bathurst, 2005, p.31). The instability of the bank has been described from the 1780 through to 1950 (Cloet, 1954) and for the period from 1887 to 2000 (Elderfield, 2001). These two accounts are brought together in the following section, with the addition of MCA data from 1997 and 2009. This, in conjunction with reference to historical charts, allows the multidecadal and even centurial evolution of the Goodwin Sands bank to be observed (Figure 4.34), and the history of exposure/burial of the site of the Stirling Castle to be followed.

The earliest chart presented here dates from 1887 and shows the Goodwin Sands as a single connected bank system with a single flow channel incised into the bank from the
south-west to towards the north-east, creating a ‘calliper’ morphology. In such a system as recorded in 1887 the wreck of the *Stirling Castle* would have fully buried as water depths at the site were 0 to \(-4\)m CD (compared to \(-15\)m CD in 2009). Taking the bedrock layer to be \(-20\)m CD, this equates to between 16 and 20m of loose sediment.

The bank split into two more discrete sections at some point between 1887 and 1965, with the northern section remaining fairly stable in position and the southern section migrating south-east by approximately 10km. The tip of the bank, as defined by the \(-10\)m depth contour, extended a further 6km south. This is the first historical chart in which we see the presence of the channel in which the wreck is now located. However, its penetration into the bank was not likely sufficient to have exposed the wreck at this time.
The water depth in 1965 was between $-4$ and $-8$ m below CD, equating to between 12 and 16 m of unconsolidated sediment.

By 1986 the depth at the site had dropped to between $-8$ and $-12$ m CD (12 - 8 m of unconsolidated sediment coverage). From 1986 until 2000 the southern section appears to have remained in a much more stable position, whilst the northern of the two sections underwent a partial split to form what can almost be termed a discrete central bank. The depth of the channel in which the wreck is situated has also remained fairly constant over this period of time.

Another way to observe the evolution of the bank is through the change in dimensions, i.e. axis length and orientation of the bank (Figure 4.35 and Figure 4.36). These variables highlight the consistent anticlockwise rotation of the Goodwin Sand bank. The tides operate in a clockwise rotation, yet the Goodwins have been rotating in an anticlockwise direction (Cloet, 1954, p.204) with the main axis migrating from 38° in the late 1700’s towards 10° in the early 2000’s (United Kingdom Hydrographic Office (UKHO) (2010, p.13), Figure 4.36). Up until 2009 the bank system has continued the trend towards a north-south alignment. However, as discussed by the United Kingdom Hydrographic Office (UKHO) (2010), this is largely due to the eastward migration of South Sand Head, while the rest of the bank system appears to be rotating in a clockwise direction away...
Figure 4.36: Goodwin Sand bank dimensions and angles for 1795 to 2009. Values for 1795 to 1947 approximated from Cloet (1954) and for 2009 extracted from MCA multibeam bathymetry.
from the north-south alignment. Consequently the western edge of the general wreck site survey area has undergone a loss of sediment on a scale of 10 - 20m from 1997 to 2009, whereas the eastern edge has undergone a period of accumulation with a net gain between 3 - 10m (Figure 4.37).

Due to the complex nature of the evolution of the bank, caution must be applied when making predictions as to the future morphological trend. Whilst the bank-scale morphological evolution can be traced through simple parameters (e.g. axis length and orientation) the presence and absence of the flood/ebb incised channels (such as the channel the Stirling Castle is presently situated within) are not forecastable using this evidence alone. Assuming the trend from 1997 to 2009 (Figure 4.38) continues we would expect to see a further burial of the wreck due to the encroachment of the bank previously found to the east of the channel and if the rate of migration of the −11m contour were to remain constant the site could be buried under 5m of sediment within the next two of decades.
Figure 4.38: Migration of the $-11\text{m CD}$ depth contour from 1997 to 2009. White ellipse marks the location of the *Stirling Castle*. Overlaid on the 2009 United Kingdom Hydrographic Office (UKHO) bathymetry.

### 4.4.1.4 Tidal currents

The maximum tidal range is 5.3m at Deal. Spring flood currents reach maximum velocities of approximately 1.6m/s in a north-northeasterly direction and 1.4m/s during the ebb tide, in a south-southwesterly direction (Figure 4.39b) (Admiralty chart 1828, tidal diamond H, location shown in Figure 4.31). Neap tidal flows are on average half the strength of the equivalent spring tidal flow (Figure 4.39a).

The nearest current measurement point to the site is located at a position more than 10km south of the site. Due to the spatial heterogeneity of the flows around the bank these data are unlikely to be representative of the flow expected at the wreck site and are, therefore, not included here.

### 4.4.1.5 Wave climate

The nearest wave buoy to the *Stirling Castle* site is the Goodwin Sands wave buoy (3km south-west of the site, location shown in Figure 4.31, water depth of 10m CD). This buoy was only deployed in mid-2008 and we have bathymetric surveys dating back to 2002. Therefore, this wave record will be supplemented with the storm surge record from the near-by Dover tide gauge (presented in the following section).
Chapter 4 Multibeam bathymetry time-series

Figure 4.39: Velocity direction and magnitude for a) neap and b) spring tidal diamond H (051°16’.3N, 001°27’.6E, 3.4km west of Stirling Castle site).

Figure 4.40: Wave directional rose for the Goodwin Sands Wave directional waverider buoy for the period of 2008 - 2014. Data from CCO.
Waves predominantly approach from the south and to a much lesser extent the north-east (Figure 4.40). A maximum significant wave height (for the period of 2008 to 2014) of 3.69m and a mean significant wave height of 0.68m were recorded (Figure 4.41). As expected there is a large seasonality in the wave record with average summer significant wave heights of 0.6m and average winter heights of 0.8m.

During the winter storms of 2013/2014 peak significant wave heights of 3.69m were observed at the Goodwin Sands buoy, equivalent to a $>1$ in 30 year storm (Channel Coastal Observatory, 2014). From October 2013 to February 2014 seven storms of greater than 1 in 1 year return period (2.8m) were observed.

### 4.4.1.6 Storm record

Using the Dover tide gauge time-series (located 20km south-west of the wreck site) the storm surge record between 1924 and 2015 can be used as a record of storminess at the site. The largest storm during survey period (2002 to 2009) was a greater than 1 in 4.5 year storm and occurred in 2007 (Figure 4.42). From April 2005 to September 2005 and from March 2006 to August 2006 (two of the MBES observational periods) no storms with return periods equal to or greater than 1 in 1 year past over the site. Over the total survey period there were a total of nine 1 in 1 year storms. Therefore, since the survey period was seven years long, this period represents a fairly typical sample in terms of the number and severity of storm events.

By comparison, the beginning of the 1990’s and the mid 1990's was fairly atypical with two $>1$ in 5 year and seven $>1$ in 1 year; and three $>1$ in 10 year and seven $>1$ in 1 year storms over these periods, respectively. The largest storm on record was observed on December $6^{th}$ 2013 and had a 1 in 843 return period and was responsible for generating wave heights in excess of 3.5m at the site (Figure 4.41a).
4.4.1.7 Sediment transport potential

Based on a critical threshold for transport of \(0.63 \text{Nm}^2\) and using the significant wave height and return period from the Goodwin Sands wave buoy time-series, wave action alone is sufficient to induce transport at the site for 6% of the time (by comparison 66% of the time at the site of the Scylla waves were sufficient for transport). This is broadly supported by Manders (2009, p.53), who observed that during model runs of the effects of a storm, storm waves did not significantly affect the pattern of residual sediment transport below the \(-10\text{m}\) depth contour. Clearly, at the site of the Stirling Castle, sediment transport is predominantly tidally induced with a net transport direction towards the north-northeast.

Using hydrodynamic models and Seazone Solutions Ltd. bathymetric surfaces Carrizales (2010) was able to forecast the sediment transport pathways of the Goodwin Sands (Figure 4.43). The average (over a 100m radius surrounding the wreck) residual transport was of 7270 kg/m/tide in a net north-northeasterly direction (22.5\(^\circ\)), in good agreement with the predominant flow direction from the tidal diamond data. The consistent net north-northeasterly transport of these model vectors demonstrates that this gulley is a flood dominant channel, unlike the neighbouring channels incised into the bank from the north which have a net sediment transport in a southerly direction.

The presence of bedforms in the multibeam bathymetry data provides evidence of the local bedload transport and can be used to give an indication of the local seabed conditions. Two main types of bedforms are observed in the region of the Stirling Castle: very large subaqueous dunes and medium subaqueous dunes, which surmount the former (Under the Ashley (1990) classification system). These medium subaqueous dunes have wavelengths of 4 - 12m and waveheights of 0.2 - 0.8m, giving a ripple index (wavelength/height) between 15 and 20 (Transect A, location shown in Figure 4.44 and transects in
Figure 4.43: Residual sediment transport direction and magnitude for the area surrounding the *Stirling Castle*, from Carrizales (2010), model run with Manning’s value of 30 and sediment grain size of 0.38mm. Overlain on the 2009 MBES bathymetry.

Figure 4.45). These bedforms are often strongly asymmetrical, with symmetry indices (stoss length/lee length) of up to 3.5. Bedforms are proximally flow aligned, with steeper faces angled towards the northeast.

The larger subaqueous dunes have heights in excess of 4m and wavelengths of approximately 250m (Transect B, location shown in Figure 4.45 and transects in Figure 4.46). These bedforms are also asymmetric with their orientation indicating a proximally northeasterly transport direction. These bedforms are observed to migrate towards the northeast along the flank of the bank to the west of the wreck site (Figure 4.47). By observing the crest and trough movement between July 2002 to April 2005, April 2005 to August 2006 and August 2006 to September 2009 a bedform migration rate circa 60m/yr is found.

### 4.4.2 Bathymetric data

Sources of geophysical data include the MCA, Archaeological Diving Unit (ADU), Rapid Archaeological Site Surveying and Evaluation (RASSE) Project and Wessex Archaeology
Figure 4.44: Location of transects A and B to the east and west of the *Stirling Castle*, respectively, overlaid on August 2006 bathymetry.

Figure 4.45: Transect through bedforms 30m to east of *Stirling Castle*. Slope removed via polynomial regression fit. Bedform peaks marked with red asterisks and troughs with green asterisks.
Figure 4.46: Transect of sandwaves 100m west of the *Stirling Castle* site of B to B'.

(WA). Where possible the original data were collated. Failing this the processed gridded data were obtained.

### 4.4.2.1 Single Beam Bathymetry

Singlebeam bathymetry surveys from 1997, 1998 and 1999 (Figure 4.48) revealed that the wreck of the *Stirling Castle* was exposed (the structure stood 4m proud of the surrounding seabed), had an associated scour pit which was at its minimum was 2m deeper than the surrounding seabed and extended at least 147m away from the wreck (the full extent was not captured by any of the three surveys) and was situated in a channel (the bathymetry sloped upwards to the east and west of the wreck).

### 4.4.2.2 Multibeam Bathymetry

Six multibeam bathymetry surveys were undertaken on the site between 2002 and 2009 (Table 4.18). The surveys for July 2002, April 2005, September 2005 and March 2006 were vertically adjusted to August 2006 and were given relative to OD. This adjustment was based on the assumption that the central wreck elevation has not changed and was performed visually using the point clouds of the two surveys being matched.

Unlike the five other MBES surveys, the 2009 MCA survey was provided relative to CD. Using datum separation values taken from the *Vertical Offshore Reference Frame* (VORF) CD values are expected to be 2.88m shallower than OD values, for the 1km by 1km area surrounding the wreck. However, assuming the elevation of the wreck has remained constant, a difference of +1.37m between the 2006 and 2009 surfaces is observed (Figure 4.49). Therefore, since the 2.88m VORF offset appears too large, even when taking into consideration the TPU of the 2009 survey which is approximately ±0.3m (Figure 4.50) and the wreck geometries appear comparable (Figure 4.49a), suggesting there
Figure 4.47: Meso-scale bed-level change at the Stirling Castle for the period of a) July 2002 to April 2005 b) April 2005 to August 2006 and c) August 2006 to September 2009. Cream colour areas represent areas which have not undergone significant changes, blues where there has been significant bed-level loss and reds where there has been significant bed-level gain. Location of wreck marked with black ellipse.
Figure 4.48: Contours of depth from the singlebeam bathymetry surveys at the *Stirling Castle* carried out in a) 1997, b) 1998 and c) 1999. Depth datum is unknown, therefore, only a relative comparison can be made.
has been little deposition or erosion occurring over the wreck structure itself, an offset of 1.37m is applied to the 2002 - 2006 data (effectively converting it to CD).

Since the raw data were provided for the 2009 survey an estimation of the a-priori TPU could be made through estimations of the uncertainty associated with each piece of equipment. From this a TPU in the range of $\pm 0.3\text{m}$ was found (Figure 4.50). Whilst this method cannot be applied to the other surveys this value seems reasonable in comparison to the estimates for the other sites’ surveys and so, shall be used for all bed-level change comparisons.

Bathymetry data for 2002, 2005 and 2006 were provided at bank scale coverage (with resolution 1 - 1.5m) and for July 2002, April 2005, August 2006 and September 2009 at wreck scale coverage (with resolution 0.25 - 1m). The highest resolution survey data available for the wreck site has a point spacing of 0.25m and was recorded in September 2005.
### Table 4.18: Metadata for multibeam bathymetry surveys of the *Stirling Castle*. Vertical offset relative to the August 2006 survey.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Contractor</th>
<th>Equipment</th>
<th>Datum</th>
<th>Vertical offset (m)</th>
<th>Area coverage (m²)</th>
<th>Area res. (m)</th>
<th>Wreck coverage (m²)</th>
<th>Wreck res. (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>July</td>
<td>ADU</td>
<td>Reson 8125</td>
<td>OD</td>
<td>4.48</td>
<td>485,000</td>
<td>1.0</td>
<td>12,900</td>
<td>0.75</td>
</tr>
<tr>
<td>2005</td>
<td>April</td>
<td>RASSE</td>
<td>Reson 8125</td>
<td>OD</td>
<td>−4.43</td>
<td>1,090,000</td>
<td>1.5</td>
<td>13,400</td>
<td>1.0</td>
</tr>
<tr>
<td>2005</td>
<td>September</td>
<td>ADU</td>
<td>Reson 8125</td>
<td>OD</td>
<td>−1.6</td>
<td>-</td>
<td>-</td>
<td>12,200</td>
<td>0.25</td>
</tr>
<tr>
<td>2006</td>
<td>March</td>
<td>RASSE, WA</td>
<td>Reson 8125</td>
<td>OD</td>
<td>−2.0</td>
<td>-</td>
<td>-</td>
<td>13,100</td>
<td>0.5</td>
</tr>
<tr>
<td>2006</td>
<td>August</td>
<td>RASSE</td>
<td>Reson 8125</td>
<td>OD</td>
<td>N/A</td>
<td>677,000</td>
<td>1.3</td>
<td>12,900</td>
<td>0.75</td>
</tr>
<tr>
<td>2009</td>
<td>September</td>
<td>MCA</td>
<td>Kongsberg EM3002D</td>
<td>CD</td>
<td>128,500,0002.0</td>
<td>13,400</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.4.3 Results

4.4.3.1 General site morphology

The general morphology of the wreck mound and associated sediment accumulation and scouring was similar for the 2002 to 2006 surveys. The wreck mound measured 50m in length and 15m in width at its widest and is relatively similar in bluffness to the Burgzand Noord wrecks. The shallowest part of the wreck stood $-12.5\text{m CD}$, so that parts of the wreck were 5.5m proud of the seabed (Table 4.19). However, on average, the wreck mound stood 3m proud of the seabed. A upstanding feature with a clear right-angle was observed at the eastern edge of the wreck, 4m in length and 0.6m in width. This feature has been identified through diver surveys as the rudder of the ship (Dunkley, 2008) and can be seen in Figure 4.51.

Local scouring was observed to the east of the wreck (down to a depth of around 1m) and downstream of the eastern end (Figure 4.52b). This local scouring is relatively restricted in its spatial extent, potentially a result of the tapering of the ends of the wreck mounds rather than the bluff ends of a cuboid on which many of the models are based.
Figure 4.51: Archaeological site plan from 2006 to 2009 *Stirling Castle* surveys from Whitewright (in review), overlaid on a hillshade of the September 2005 survey.

Table 4.19: Wreck morphology of the *Stirling Castle* for 2002.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth at wreck site, CD</td>
<td>−18m</td>
</tr>
<tr>
<td>Max. height above seabed</td>
<td>5.2m</td>
</tr>
<tr>
<td>Mean height above seabed, H</td>
<td>3.3m</td>
</tr>
<tr>
<td>Wreck beam</td>
<td>19m</td>
</tr>
<tr>
<td>Wreck length</td>
<td>51m</td>
</tr>
<tr>
<td>Across flow width, W</td>
<td>50m</td>
</tr>
<tr>
<td>Orientation</td>
<td>273.5/93.5°</td>
</tr>
<tr>
<td>Angle of attack</td>
<td>80°</td>
</tr>
<tr>
<td>W:H</td>
<td>17</td>
</tr>
<tr>
<td>Scour pit area</td>
<td>20800m²</td>
</tr>
<tr>
<td>Scour orientation</td>
<td>49°</td>
</tr>
<tr>
<td>Max scour length</td>
<td>267m</td>
</tr>
<tr>
<td>Max scour width</td>
<td>85m</td>
</tr>
<tr>
<td>Max scour depth</td>
<td>3.1m</td>
</tr>
<tr>
<td>Average slope within scour pit</td>
<td>3.7°</td>
</tr>
</tbody>
</table>
Chapter 4 Multibeam bathymetry time-series

Figure 4.52: Schematic of the spatial extent of scouring and deposition at the 
Stirling Castle for a) July 2002, b) April 2005, c) August 2006 and d) September 
2009. As with the BZN site (Section 4.3.3.1), here too the output from the fill 
too was cleaned to remove features not associated with the wreck site.
The maximum scour depth, relative to the ambient seabed, was 3m and was observed over 40m downstream of the wreck. The singular wake scour pit extended 295m downstream of the structure and is aligned towards 67°. Since the structure is aligned 80° to the flow we would expect to observe a scour pit at both ends of the structure emanating downstream with a region of deposition in-between (Dix et al., 2007). The singular scour pit observed here is more analogous to models where the structure is aligned 67.5° to the flow. It is feasible that the tidal diamond data do not capture the local current conditions at this site and that the flow is aligned more towards 45°, congruent with the alignment of the dunes observed in the wider area bathymetry (Figure 4.47).

Similarly to the BZN 3 wreck, there is an area of sediment deposition updrift of the Stirling Castle extending some 26m upstream of the wreck mound. Utilising the same assumption as before (length of accumulation = H/tan(α)), but this time using an angle...
of 4° (the gravel composition at the site should be capable of supporting steeper angled slopes; Dix et al., 2007) then the estimated length of accumulation is 43m, 17m longer than observed. Therefore, it is likely that the coarse material is capable of supporting slope angles in excess of 6° in this region of accumulation.

Approximately 150m south-east of the wreck a small mound is visible within the area-scale surveys (Figure 4.47a and b), this feature was also visible within a later magnetometer survey and was interpreted as a separate wreck to the Stirling Castle (Wessex Archaeology, 2010).

Following the RASSE project surveys from 2002 - 2006 the next survey over the wreck was conducted in September 2009 (Figure 4.53f and Figure 4.52d). This survey revealed a significantly different wreck site morphology. The wreck stood 1.7m proud of the seabed (a reduction in height of 1.3m). The downstream scour still remained, but had a reduced maximum depth of 1.6m, relative to the ambient area and was much reduced in both length (100m, previously 295m) and width (21m, previously 85m). The wreck mound itself also appeared narrower by approximately 2.5m, which could have been due to increased burial. The site still slopes upward towards both the east and west. Therefore, during this period of time the wreck was still positioned within the channel.

4.4.3.2 Bed-level change

The evolution of the Goodwin Sands bank has already been quantitatively described by comparing both singlebeam and multibeam bathymetry data sets (Figure 4.37) and on a meso-scale (coverage 500,000m² and a resolution 1 - 1.5m) through bed-level change plots (Figure 4.47). Such an approach can also be applied at a smaller-scale to consider site scale (coverage of 13,000m² and resolution 0.25 - 0.75m) changes for the period between 2002 to 2009.

The most striking difference between the 2002 and 2005 bathymetry surveys (Figure 4.54a) is the extensive bed-level loss which is observed within the downstream scour pit with values greater than 2m of loss. Half a metre of bed-level loss is also observed at the western end of the wreck, extending 10m upstream of the wreck. Whilst, at the eastern end of the wreck, a gain of 0.5m was observed. Downstream of the eastern tip of the wreck accumulation occurred, so that the bed-level was 2.5m higher in 2005 than in 2002. The stimulus for this bed-level change is not obvious. Since there are no storms on record for this period of time (Figure 4.42) it is unlikely that this change is due to wave induced transport. Instead it is postulated that the migration of the bank may have altered the local flow direction more towards the east so that the angle of attack is decreased thus increasing the maximum total kinetic energy and scour depth downstream of the wreck (Dix et al., 2007).
Figure 4.54: Wreck-scale bed-level change at the Stirling Castle from a) July 2002 to April 2005 b) April 2005 to September 2005 c) September 2005 to March 2006 d) March 2006 to August 2006 and e) August 2006 to September 2009. Cream colour areas represent areas which have not undergone significant changes, blues where there has been significant bed-level loss and reds where there has been significant bed-level gain.
Over the period of five months from April 2005 to September 2005 (when significant wave heights were consistently below the threshold for sediment transport, Figure 4.41b) most of the wreck site underwent very little significant change (Figure 4.54b). Bed-level change is restricted to the western and eastern ends of the wreck, and is opposite and equal to the change from 2002 to 2005, i.e. there was some restoration towards the level in 2002. Downstream of the western end of the wreck, slightly outside of the scour region, bed-level loss is observed with values in the region of 0.3 - 0.7m. Downstream of the eastern end, also slightly outside of the main scour pit, there is an area of bed-level gain with values of approximately 0.5m.

Bed-level loss, for the period of September 2005 to March 2006 (Figure 4.54c), at either end of the wreck once again occurred in opposite directions, bed-level loss was observed at the eastern end (0.3 - 2.0m) and bed-level gain was observed at the western end (0.3 - 0.9m). Downstream of the wreck three strips of flow-aligned accumulation occurred atop what were already small ridges of sediment deposition, thus increasing the height of these features.

For the period between March 2006 and August 2006 (Figure 4.54d) there is an isolated downstream stretch of bed-level loss emanating from the eastern end of the wreck and a small amount (0.3m) of sediment gain along the northern, downstream, side of the wreck. To the east of the wreck there is an increase in bed-level between the values of 0.3 and 1.3m, which is likely to have resulted from the westward encroachment of the channel edge over this period of time.

Over the entire RASSE observation period, 2002 - 2006, there was a net deposition of sediment within the wreck area of $8,830 \pm 2,500m^3$. When observing each period of time separately (Figure 4.54) this change is not initially apparent as there is a large spatial variability in this pattern which is often masked by bedform migration and localised change surrounding the wreck structure.

Over the final period for which multibeam data of the wreck site are available, from August 2006 to September 2009 (Figure 4.54e), a exceptionally large increase in bed-level is observed across the whole wreck site. On average bed-level gain across the site was 2m over the three year period. However, large areas where more than 3m of bed-level gain occurred are observed to the east of the wreck and downstream of the wreck, where previously there had been a downstream scour pit. To the north-west of the site there is an isolated area of bed-level loss associated with the migration of a sandwave. This 100’s metres scale accumulation is as a direct result of the evolution of the sandbank system, as described in Section 4.4.1.3. From 2002 to 2009 the western margin of the bank to the east of the wreck (delineated by the $-12m$ depth contour) migrated by 130m in a west-northwesterly direction.
4.4.3.3 Maximum and Minimum Depth Locations

The evolution of the wreck site can be observed through bed-level change plots (Section 4.4.3.2) as well as through the presentation of the maximum and minimum depth locations, which highlight the peak of the wreck structure and the trough of the scour pit, respectively (Figure 4.55). Whilst the position of the shallowest depth atop the wreck has remained fairly constant year-on-year (within a 1m radius), with the exception of April 2005, where the wreck mound peak is found 5m north-west of the other years, a much larger variability in the location of the maximum scour depth is observed. Initially the maximum depth is found 62m north-east of the wreck. This then migrates south-west year-on-year at a rate of 5m/yr. A shift of 20m is observed from August 2006 to September 2009, bringing the deepest point of the scour pit to just 28m exactly north of the wreck.

![Figure 4.55: Positions of maximum depths within scour pit and minimum depths atop wreck for each multibeam bathymetry survey of the Stirling Castle, overlaid on 2009 bathymetry. Maximum scour pit depth given in brackets.](image)

It has been observed that for structures orientated obliquely to the flow scouring is more extensive downstream for the end orientated into the flow (Quinn, 2006). As the wreck structure has not changed in its orientation this then suggests that the flow has moved more towards the east-northeast. This is likely to also be connected to the rotation of the channel in which the wreck is positioned from 23° in 1997 (79° to the orientation of the wreck) to 52° in 2009 (48° to the orientation of the wreck), a rate of 2.4°/yr.

Through the deposition of material in the area surrounding the wreck the shipwreck structure went from being on average 3.3m proud of the seabed in 2002 (W:H of 17) to on average just 1.5m proud in 2009 (W:H of 29). Saunders (2004) observed that an obstacle aligned 67.5° to the flow had a maximum length of wake scour of 17 times the height.
of the obstacle. Using this empirical observation the predicted scour length for the wreck in 2002 would be 56m and in 2009, 25.5m. Whilst the observed maximum scour length for both of these periods is far greater than this estimates (295 and 103m, respectively) the distance of the maximum scour depth away from the wreck for these periods (59 and 24m, respectively) are within 3m of the estimated values, i.e. the relative change in distance of maximum scour depth is in good agreement with the observation’s of Saunders (2004).

4.4.4 Discussion

The *Stirling Castle* is positioned within a flood-dominant channel, at a depth beyond the reach of wave-induced oscillatory motion. The pattern of observed wake scouring (a single scour pit emanating from the end of the structure oriented upstream) is consistent with physical modelling results of a cuboid orientated 67.5° to the prevailing flow (Dix et al., 2007). As is the relative decrease in scour length and depth from 2002 to 2009 associated with the decrease in wreck height due to the increase in the bed-level of the surrounding seabed. Local scouring is restricted to the stern of the wreck, downstream of the prominent rudder assemblage. This perhaps indicates that the rudder assemblage is in itself acting as a nucleus for scour, in a similar way to the artefacts at the *Queen Anne’s Revenge* site (McNinch et al., 2006).

From the analysis of these data it is clear that the Goodwin Sands bank is a very complex system which operates on a full range of time-scales, from medium subaqueous dunes which migrate at a rate of around 60 metres per year, to the bank system as a whole, which rotates at a rate of less than a degree per decade. Medium to small scale geomorphological processes are captured within the wreck site MBES survey extent and their impact of the wreck site’s taphonomy can be relatively well constrained. Studying the bank scale evolution required a far more extensive bathymetric and historical time-series both in terms of its spatial extent (24 by 10km) and its length (historical data back to the 1795 were utilised). Even with this dataset although the large scale evolution of the bank follows a predictable trend the smaller scale details (i.e. the position of the incised channels) are less easy to forecast.

4.5 *Algerian*

In this section a multibeam bathymetry time-series composed of six high-resolution and two lower-resolution repeat surveys spanning 13 years of the wreck of the *Algerian* (National Monuments Record 805629), located in the West Solent (Figure 4.56), is presented.
Figure 4.56: Location map of wreck of the *Algerian* and the nearest tidal diamond and wave buoy, overlain on 2006 and 2011 MBES surfaces (Contains public sector information, licensed under the Open Government Licence v2.0, from MCA).
4.5.1 Site Description

The wreck of the *Algerian* (Figure 4.57) is situated approximately 1.25 km north-west of Gurnard, Isle of Wight, at a position of 617114E 5625303N (UTM Zone 30N) and a depth of −20 to −22 m CD (CD is 2.73 m below OD). The wreck structure measures 104 m long, 28 m wide, aligned 71/251° (True) and stands proud of the seabed by 6.5 m at its highest point. Service pipelines and cables, which cross from Lepe on the mainland to Cowes on the Isle of Wight, pass within a few metres of the *Algerian*. Although there is no deep draft shipping through the western Solent there is still considerable shipping traffic over the wreck site, which dissuades some from recreationally diving at the site (Wight Spirit Diving Charters, 2015).

![Figure 4.57: A photo of the Algerian.](PhotoShip, 2015)

4.5.1.1 Archaeological context

The *Algerian*, originally named *Flintshire*, was built in 1896 by the Sunderland Shipbuilding Company and made up part of the Shire line (Tennent, 2006, p.78). She had a tonnage of 3815 grt, length of 111 m, beam of 13 m, hull depth of 28 m and a service speed of 10 knots (Merchant Navy Association, 2015). Following 21 years of service she was bought by the Royal Mail Steam Packet Co., where she remained for six years before being purchased by the Ellerman Line Ltd to make up part of the Levant service, under the name *Algerian*.

At 8.20 am on the 12th January 1916 the *Algerian* departed from Cowes Road, Isle of Wight, heading for Avonmouth (Figure 4.58) (Maritime Archaeology Trust, 2015). After travelling just 26 km along her greater than 600 km journey, at 10:15 am, she hit a mine 2.5 miles south-west of the Needles. It was later determined that this mine had been laid by the German submarine, UC-5. The contact mine exploded on her starboard side, abreast of No. 2 hatch (Larn and Larn, 1995, p.45). All of the crew bailed into three
lifeboats. However, after realising the vessel wasn’t sinking the captain and a few other members of the crew re-boarded (Maritime Archaeology Trust, 2015). For now the flooding was contained to just holds No. 1 and No. 2.

Three Admiralty armed drifters responded to distress signals, as well as the SS Warden, a Trinity House vessel, which assisted in the tow for Southampton, as did the tug Walvisch. By 2pm the vessel was approaching the boom defence near Cowes (Maritime Archaeology Trust, 2015). The tide was running strong and there were concerns that the Algerian was set on course to collide with the boom vessel, Magda. As a result the Algerian was ordered to drop anchor.

The No. 1 bulkhead finally gave way as the ship came to a standstill (it is not known whether or not this was a direct result of letting the anchor go). Attempts were made at securing tows to the beach, but these failed as the ship started to rapidly sink, bows first, causing the crew to again abandon ship. The vessel sank on her port side into a deep water channel to a depth of −22m CD just one mile off Egypt Point at a time of 2:30pm (Larn and Larn, 1995). Fortunately all crew made it off the ship safely and the ship was in ballast at the time, so there was no cargo to retrieve (Tennent, 2006, p.78).

Originally a diver was to be sent down to the wreck to ascertain the cause of the explosion (it was not yet confirmed to be a mine). However, the loss of the HMT Albion II to a mine near the Needles the following day is thought to have satisfied the Admiralty that a mine was the cause, since there is no record of a diver ever visiting the wreck (Maritime Archaeology Trust, 2015). The wreck, like many others, lay undisturbed until the end of the war.

The wreck originally protruded to a least depth of −8.2m and a light buoy marked the position of the hazard from 1924 (United Kingdom Hydrographic Office (UKHO), 2015).
She was first dispersed in 1920 and again in October 1925 to a least depth of $-14.7\text{m}$, i.e. $6.5\text{m}$ of height were removed from her structure. In March 1951 she was drift swept clear at $-15.2\text{m}$, but fouled the line at $-15.5\text{m}$. By 1978 the wreck, reportedly, stood just $5.6\text{m}$ tall and a $1\text{m}$ deep scour pit had formed around the structure (United Kingdom Hydrographic Office (UKHO), 2015). Although the ship had a beam of just $13\text{m}$ the wreck structure in 1978 measured $30\text{m}$ wide, suggesting that the ship lies directly on her side, and is consistent with the vessel’s hull depth of $28\text{m}$.

Ten years later the site was resurveyed and the previously observed scour had infilled, it was also observed that the structure stood $6.7\text{m}$ proud of the seafloor ($1.1\text{m}$ taller than in 1978) (United Kingdom Hydrographic Office (UKHO), 2015), this suggests that the 1978 measurement was an underestimation since it is unlikely to have grown in height.

### 4.5.1.2 Geological setting

The West Solent was once the valley for the Solent River (Figure 4.56), which flowed from west to east prior to the Flandrian Transgression. An extensive seabed covering of coarse, angular, sediment has been observed, these are thought to have derived from Quaternary plateau gravels (Langhorne et al., 1982). Gravel and sand deposits range in thickness from $2 - 3\text{m}$ in the West Solent (Langhorne et al., 1982).

Grab samples from the West Solent ($\approx 10\text{km}$ south-west of the wreck site) have revealed a strongly bimodal distribution of sediment sizes with peaks at $1 - 2\text{mm}$ (very coarse sand) and $8 - 27\text{mm}$ (medium pebbles). On average $20\%$ of the sample was composed of sand (Langhorne et al., 1982).

### 4.5.1.3 Tidal conditions

Spring tidal ranges are approximately $3.4\text{m}$ (UKHO chart 2036). The closest tidal velocity data come from a tidal diamond data from $2.3\text{km}$ south-west of the wreck site Figure 4.59. Tides in the West Solent are strongly rectilinear. Tides flood towards the north-east ($65^{\circ}(\text{True})$) and reach a peak velocity during the spring phase of $1.7\text{m/s}$, whereas, during the neap phase, flood velocities peak at $0.85\text{m/s}$. During the ebb phase of the tide, which is slightly shorter than the flood phase, tidal currents flow towards the south-west ($244^{\circ}(\text{True})$) and peak at $1.75\text{m/s}$ during the spring cycle ($0.05\text{m/s}$ faster than the flood phase) and $0.9\text{m/s}$ during the neap phase ($0.05\text{m/s}$ faster than the flood phase).

During their campaign to study the mobility of seabed gravel in the West Solent Langhorne et al. (1982) observed a maximum tidal current at $1\text{m}$ above the seabed of $1.22\text{m/s}$ in the direction of $170^{\circ}$ and $0.99\text{m/s}$ in $10^{\circ}$. Supporting the ebb dominance observed in the tidal diamond data.
Divers have observed that the wreck frequently acts as a nucleus for the collection of traffic cones, patio chairs, drinks cans etc. (Wight Spirit Diving Charters, 2015). This could be an indicator that the wreck is situated at a site of a convergence of opposing currents or that the wreck acts as a barrier to the transport of these items.

### 4.5.1.4 Wave conditions

The narrow western entrance to the Solent, just 1.5km at its widest, shelters the wreck site from long period surface waves (Langhorne et al., 1982). As a result wave generation within the Solent is not sufficient to generate high orbital velocities.

Whilst the nearest wavebuoy to the wreck site is the Lymington buoy (just 12km south-west of the site, water depth 3m CD), the time-series for this site covers only the years of 2008 - 2011 and 2014 (Figure 4.60). Therefore, to fill in the gaps in data, a time-series from the Milford-on-Sea wave buoy (20km south-west of the site, water depth 10m CD), which also includes directionality, is also included. Due to the Lymington buoy’s position, further up the Solent channel, significant wave heights at this site are approximately 22% the height of those passing over the Milford-on-Sea buoy (Table 4.20 and Table 4.21). The period of the wave at Lymington is also a third of the length of those waves passing over the Milford-on-Sea buoy.

On average (from 2003 - 2015) significant wave heights at the Lymington buoy are 0.15m and peak at 0.7m (99.95% quartile). Waves predominantly approach from 210°(True) (Figure 4.61) and enter the site along the western Solent channel approaching from the south-west. The prevailing direction of the waves at the Milford-on-sea site will be affected by the presence of land to the east of the site preventing waves approaching from
this direction. However, it is still unlikely for waves to come from the east at the Algerian site since they would have to travel up the eastern Solent and refract around Cowes in order to reach the site.

Langhorne et al. (1982) reported that the wave exposure of the West Solent was ‘none’. Despite this littoral processes were still observed and gave rise to longshore transport of sediment from west to east (Langhorne et al., 1982).

Taking a minimum depth of the site to be 20m waves would only be large enough to produce an oscillatory velocity at the seabed when greater than 2m in height (Soulsby, 1997). During the entire Lymington time-series no waves with significant heights of greater than 0.9m are observed and even a 1 in 200 year storm would not be sufficient to generate waves of this height (Table 4.20).

<table>
<thead>
<tr>
<th>Return period (years)</th>
<th>Significant wave height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.29</td>
</tr>
<tr>
<td>10</td>
<td>1.45</td>
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<tr>
<td>100</td>
<td>1.60</td>
</tr>
<tr>
<td>200</td>
<td>1.64</td>
</tr>
</tbody>
</table>

Table 4.20: Storm return periods for Lepe wave buoy. Based on hindcast HR50 (New Forest District Council, 2010).

<table>
<thead>
<tr>
<th>Return period (years)</th>
<th>Significant wave height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.7</td>
</tr>
<tr>
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<tr>
<td>20</td>
<td>4.7</td>
</tr>
<tr>
<td>50</td>
<td>5.0</td>
</tr>
<tr>
<td>100</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Table 4.21: Storm return periods for Milford-on-Sea wave buoy. Based on CCO wave buoy data.

More than five individual storm events occurred towards the end of 2013 and in early 2014, one of which had a greater than a 1 in 10 year return period (Figure 4.60). Therefore, if storms were to have an impact on the wreck site (e.g. through the enhancement of peak tidal currents) we would expect to see a larger change in the bed-level surface between the 2013 and 2014 surveys than between any other surveys.
Figure 4.60: Time-series of significant wave height at Lymington (orange) and Milford-on-Sea (blue) wave buoys. Horizontal dashed line indicates the 99.95% quantile. Vertical continuous lines indicate the dates of survey. Data courtesy of the CCO.

Figure 4.61: Wave rose of mean significant wave height and direction at the Milford-On-Sea wave site from 2002 to 2014. Data courtesy of the CCO.

4.5.1.5 Sedimentary processes

Within the Algerian multibeam bathymetry data bedforms are prevalent below the −20m CD contour and are aligned perpendicular to the tidal flow (north-west to south-east). These bedforms have wavelengths ranging from 5 to 10m and waveheights are approximately 0.5m; medium-subaqueous dunes under the Ashley (1990) classification system.

Figure 4.62 shows the inferred bedform transport direction based on the asymmetry of the bedforms, performed using the quantitative automated bedform method of Cazenave (2012). Bedform asymmetry has a bimodal distribution; to the east of the wreck, above
the −22m CD depth contour, transport is in a predominantly northeasterly (flood) direction. Whereas, to the north, west and south of the wreck bedform asymmetry indicates a net southwesterly (ebb) migration.

![Figure 4.62: Bedform asymmetry direction from the automated bedform analysis on the 2006 MBES data. Calculated by Cazenave (2012). Selected subset size was 200m, allowing bedforms with wavelength below 40m to be analysed. Areas with no results are those identified as being flat beds. Outline of Algerian in white.](image)

Using hydrodynamic (TELEMAC-2D) modelling Teles (2003) estimated the residual current for the Solent region. In the West Solent residual currents were towards the northeast (60°) with velocities of 0.12 and 0.09 m/s over the spring and neap tide, respectively. However, in her synthesis of the bedload transport based upon the tidal asymmetry, maximum and mean bed shear stress, Teles (2003) denoted that the northeastern end of the West Solent channel was an area of eddies. This seemingly complicated pattern of tidal currents and inferred transport prompts further analysis based on the migration of bedforms between MBES surveys.

Through tracing the bedform crests (Figure 4.63) the lack of migration of these bedforms is observed (migration between surveys is on average within the x/y uncertainty of surveys). This suggests that whilst currents are sufficient for bedload transport (i.e. bedforms are present) the tidal asymmetry is insufficient to induce a strong residual transport in either the ebb or the flood tidal direction. This inference is supported by the lack of bed-level change over a region neighbouring the wreck (Figure 4.64). The change between these two surveys is largely dominated by the presence of clear survey artefacts (track-aligned bands of bed-level change). However, there are localised areas of change which likely the result of real processes. For example, the northwestern coastline of the
Isle of Wight gained over 5m in height over the four year period. On the whole the bed appears to be very stable on a multi-annual scale with no obvious large scale feature migration, much like the site of the *Scylla* (Section 4.12).

### 4.5.2 Bathymetric data

Six high-resolution MBES surveys of the wreck of the *Algerian* were collated, details of each survey are given in Table 4.22. Additionally a 2002 survey collected using a GeoSwath system and a 2006 MCA survey are included. However, these were only available pre-gridded at a lower resolution (1m and 2m, respectively) and therefore, cannot be used to quantify the bed-level change or volume change around the wreck site.

Ideally, Calshot tide gauge data would be used to correct all surveys as this gauge is far closer to the site (just 10km north-east of the wreck site) than the Portsmouth tide gauge (>15km from the wreck site). However, as the Calshot time-series is just three years long, it cannot be used to correct the 2012 survey data. An attempt was made to use the Calshot time series to reconstruct the tide outside of the 3 year window. However, the length of the time-series was insufficient to provide a good estimate of the tidal elevations (Figure 4.65). Therefore, for those periods of time where the Calshot elevation data are not available (i.e. the 2012 survey) the Portsmouth tide gauge data is used instead, incurring a maximum error at high tide of 0.3m (high tide is consistently higher at the Portsmouth tide gauge and low water is consistently lower, i.e. Portsmouth has a larger tidal range). As the 2012 survey was taken during high tide we can expect to observe that our computed depths for this survey will be consistently too shallow.
Figure 4.64: Bedlevel change from 2002 to 2006 for the wider area surrounding the wreck of the Algerian. Location of wreck and ambient area used in bed-level change analysis shown.

Table 4.22: Survey details for the six repeat high-resolution multibeam bathymetry surveys and two lower resolution, pre-gridded surveys of the Algerian.

<table>
<thead>
<tr>
<th>Date</th>
<th>Coverage (km²)</th>
<th>Sonar system</th>
<th>Position and orientation system</th>
<th>Average point spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>6.8</td>
<td>GeoSwath</td>
<td></td>
<td>1.00 (Gridded)</td>
</tr>
<tr>
<td>25th July 2006 (MCA)</td>
<td>29.0</td>
<td>-</td>
<td>-</td>
<td>2.00 (Gridded)</td>
</tr>
<tr>
<td>24th February 2012</td>
<td>3.2</td>
<td>SeaBat®7101</td>
<td>POS MV V4 DGPS</td>
<td>0.21</td>
</tr>
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<td>22nd February 2013</td>
<td>2.6</td>
<td>SeaBat®7101</td>
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<tr>
<td>25th February 2013</td>
<td>1.6</td>
<td>SeaBat®7101</td>
<td>POS MV V4 DGPS</td>
<td>0.21</td>
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<tr>
<td>1st May 2013</td>
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<td>SeaBat®7101</td>
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<td>26th March 2014</td>
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<td>POS MV V4 DGPS</td>
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<tr>
<td>16th March 2015</td>
<td>0.3</td>
<td>SeaBat®8125</td>
<td>POS MV V4 DGPS</td>
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</tr>
</tbody>
</table>
The only survey for which a sound velocity profile was recorded and provided with the data was for the 2015 survey (average sound velocity of 1478.3m/s). As all surveys were performed during late winter/early spring it is predicted that the water column will be fairly well mixed and homogeneous in terms of sound velocity. Therefore, the same profile is used for all six surveys.

Patch test data were not supplied with any of the surveys. As a result, roll, pitch and yaw offsets had to estimated using data over the wreck area. In some years the survey design was non-ideal for constraining yaw which requires adjacent survey lines in the same direction.

Ranges of roll, pitch and heave are marginally larger for the 2012 survey and the first 2013 survey (22nd April) (Table 4.23). This has been linked to rougher seas (Ernstsen et al., 2006a) and could mean that the data from these surveys have larger errors.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Heave range (m)</th>
<th>Pitch range (°)</th>
<th>Roll range (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24th February 2012</td>
<td>1.9</td>
<td>3.6</td>
<td>7.0</td>
</tr>
<tr>
<td>22nd April 2013</td>
<td>0.8</td>
<td>7.5</td>
<td>10.4</td>
</tr>
<tr>
<td>25th April 2013</td>
<td>0.3</td>
<td>2.8</td>
<td>6.8</td>
</tr>
<tr>
<td>1st May 2013</td>
<td>0.3</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>26th March 2014</td>
<td>0.4</td>
<td>3.2</td>
<td>2.8</td>
</tr>
<tr>
<td>16th March 2015</td>
<td>0.2</td>
<td>1.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Whilst the most obvious choice for the survey to which the others should be corrected to is the 2015 survey, since it is the most recent and uses the most up to date equipment and methods, this survey appears to be exactly 0.22m deeper than the MCA 2006 survey.
and the 2014 survey. Similarly the 2012 survey and the three surveys in 2013 are consistently shallower (by 0.13m to 0.55m). Therefore, all surveys shall be corrected relative to the 2014 survey, which also has the advantage that it covers a much larger area than the 2015 survey. As a result, more robust estimates of offsets can be made.

As there are no areas of exposed bedrock in close proximity to the wreck, pipelines and the wreck structure were used to determine any vertical and horizontal offsets between surveys, these are given in Table 4.24. Vertical offsets were easily constrained (very tight, unimodal, histograms of bed-level change with small values of standard deviation when compared to 2015 survey). These were likely errors in the collection and processing of the MBES data, as for example, it is unlikely that the 500,000m$^2$ survey area underwent a consistent elevation decrease by 0.17m over three days between the the surveys on the 22nd and 25th April 2013. Therefore, offsets in the vertical could be corrected for with the addition of a fixed value given in Table 4.24.

When attempting to correct for horizontal offsets, residuals were consistently greater than the required shift (RMS$>1$m). Therefore, as offsets could not be fully constrained, no horizontal offsets were applied to the data. As a result any horizontal changes between surveys of less than 1m cannot be resolved using these data.

Table 4.24: Vertical and horizontal offsets relative to the 2014 Algerian MBES survey. Where x and y are positive values the survey had to be shifted east and north and where x and y are negative values the survey had to be shifted west and south.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Vertical offset (m)</th>
<th>Horizontal x offset (m)</th>
<th>Horizontal y offset (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 2002</td>
<td>1.43</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>25th July 2006</td>
<td>0.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>24th February 2012</td>
<td>0.09</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>22nd April 2013</td>
<td>-0.16</td>
<td>-1.2</td>
<td>0.5</td>
</tr>
<tr>
<td>25th April 2013</td>
<td>-0.33</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>1st May 2013</td>
<td>-0.13</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>26th March 2014</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16th March 2015</td>
<td>0.22</td>
<td>0.9</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

Average survey point spacing for the six most recent surveys was just 0.18m (Table 4.22). This largely resulted from the uniform survey pattern with minimal swath overlap. The exception being the 2015 survey where a star-shaped pattern produced a superior resolution of a sounding every 0.1m.

A grid spacing of 1m spacing was used during the DoD analysis as the minimum mean point spacing was 0.25m and the minimum required number of points per cell to calculated roughness is 4. Therefore, a point spacing of 1m was sufficient for roughness to be estimated and was sufficiently high to prevented information from being lost.
To provide context to the high-resolution bathymetric surveys, which at most cover a 0.33km² patch of the seafloor, the June 2006 MCA survey is utilised. This covers a 29.0km² area at a resolution of 2m and to a maximum allowable total vertical uncertainty of ±0.6m and maximum allowable total horizontal uncertainty of 6m (International Hydrographic Organisation (IHO), 2008) Figure 4.56.

Since the original surveys covered areas in excess of 3km² file sizes were too large (greater than 1GB) to run through certain ArcMap tools, e.g. coincident points. Therefore, a subset of area 0.5km² (1km by 0.5km) was used during the DoD analysis.

Estimates of the $\text{LoD}_{\text{min}}$ were made through comparing the elevation differences between surveys for an area of seafloor outside of the area of influence of the shipwreck (Table 4.25, location shown in Figure 4.64). The $\text{LoD}_{\text{min}}$ value ranges between ±0.05m and ±0.16m. A threshold of ±0.2m is used throughout the analysis, as, described previously, the threshold can only sensibly be resolved to one decimal place.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Net ambient bed-level change with vertical offset applied (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002 - 2006</td>
<td>±0.07</td>
</tr>
<tr>
<td>2006 - 2012/02/24</td>
<td>±0.05</td>
</tr>
<tr>
<td>2012/02/24 - 2013/04/22</td>
<td>±0.08</td>
</tr>
<tr>
<td>2013/04/22 - 2013/04/25</td>
<td>±0.05</td>
</tr>
<tr>
<td>2013/04/25 - 2013/05/01</td>
<td>±0.16</td>
</tr>
<tr>
<td>2013/05/01 - 2014/03/26</td>
<td>±0.11</td>
</tr>
<tr>
<td>2014/03/26 - 2015/03/16</td>
<td>±0.07</td>
</tr>
</tbody>
</table>

4.5.3 Results

4.5.3.1 General description

The wreck of the *Algerian* is positioned within the inner meander bend of the Solent River paleochannel. The wreck presents an across flow width of 28m and has an average height of 2m above the seabed, giving the structure a W:H of 11 (Table 4.26). The wreck structure itself is made up of three distinct sections (Figure 4.66c), making up a total length of 105m (6m shorter than the original ship specifications). The south-western end (the stern) is 15m in length and 10m at its widest. The central section stands most proud of the seabed with a large cuboid structure on the southern side of the wreck and a very discrete smaller turret like feature on the northern side measuring 4m by 4m by 3m. At the north-eastern end of the wreck, the bow, appears quite detached from the rest of the
wreck. On the whole the wreck tapers in elevation downward towards the north-eastern end (Figure 4.66c) end. Just 12m to the south-east of the north-eastern end of the wreck there appears to be a separated fragment of wreck measuring 7m in length (Figure 4.66a) a further isolated fragment of wreck to north of south-western end 6m away from the main structures, measuring 1.8m by 1.8m and 0.6m in height. These two fragments are just about visible in all surveys except the lower resolution 2006 survey and have not significantly altered in their position.

Table 4.26: Wreck morphology of the *Algerian*.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth at wreck site, CD</td>
<td>−22m</td>
</tr>
<tr>
<td>Max. height above seabed</td>
<td>6.5m</td>
</tr>
<tr>
<td>Mean height above seabed, H</td>
<td>2.5m</td>
</tr>
<tr>
<td>Wreck beam</td>
<td>28m</td>
</tr>
<tr>
<td>Wreck length</td>
<td>105m</td>
</tr>
<tr>
<td>Across flow width, W</td>
<td>28m</td>
</tr>
<tr>
<td>Orientation</td>
<td>251/71°</td>
</tr>
<tr>
<td>Angle of attack</td>
<td>6°</td>
</tr>
<tr>
<td>W:H</td>
<td>11</td>
</tr>
</tbody>
</table>

Two areas of discrete scouring are present at the wreck site (Figure 4.67), these are located at the south-western tip of the wreck, where depths are 1.15m deeper than the surrounding bed (consistent with 1978 UKHO observations of scouring occurring to a depth of 1m) over an area 3.6m away from the wreck and 17m along the wreck structure and to a lesser extent, at the north-eastern tip where the sea-bed has scoured to a depth of 0.3m over an area 3.5m in width and 6m in length. No areas of wake scour are observed downstream of the wreck at any point during the time-series.

Bedforms are deformed to 250m north-east of the site. At the centre of this deformation the bed is slightly raised (by a maximum of 1.5m) creating a downstream ridge orientated 52° and to much lesser extent (approximately 50m) to the south-west of the site (maximum height of 1m above the ambient seabed) with the deformation in the bedform crests continuing outward from the wreck in the direction of 225°. These areas of sediment deposition and bedform deformation are aligned downstream of the wreck relative to the ebb and flood tide (i.e. the feature to the north-east would form during the flood tide and the feature to the south-west during the ebb tide). These features do not conform to the models of Dix *et al.* (2007), which suggest that a flow aligned obstacles should form a singular local scour pit at the upstream end and a single wake scour pit at the downstream end, with only a restricted region of deposition forming at the downstream end.
Figure 4.66: Point cloud from the 2015 survey of the wreck of the *Algerian* proximally looking towards the a) north-west b) south-east c) south-west and d) north-east. Trihedron indicates up (blue), north (green) and east (red). Vertical exaggeration of 2. Ambient occlusion performed using qPCV plugin. Horizontal scale maintained throughout.
The presence of an area of deposition in alignment with the wreck can be explained, fairly simply, in terms of shear stress distribution. Due to the width of the structure (W:H in excess of 6) it is anticipated that two vortices will form downstream of the structure (Lambkin et al., 2006). Further downstream of the structure these two vortices coalesce. The region where the two vortices remain separated (the shadow region) will have a lower shear stress. As a result, any sediment taken into suspension by the vortices will be deposited here. This does not, however, explain why no regions of scour are observed either side of the area of deposition. It is postulated that this is a result of a difference in sediment composition between the sediment deposited in the wake of the structure and the sediment making up the surrounding bed. For example, were there a small supply of sands in the region these could be taken into suspension by the accelerated flow around the wreck and become deposited within the shadow region. Feasibly, the gravel bed may be too coarse to be transported by suspension, thus no scouring is observed.

The deformation of the bedforms downstream of the structure could result from the reduction in bedform migration rate downstream of the structure, as observed by Sutton
and Neuman (2008), who noted, through the use of physical models, that downstream of surface mounted cylinders when an upstream supply of sediment is present (live-bed conditions) sand bedforms migrated more slowly than in the ambient surrounding area, resulting in a convex deformation of the bedform crest towards the cylinder.

Excluding two surveys (2012 and 2013/04/22) the location of the maximum scour depth at the Algerian remained within a 2m radius (Figure 4.68). By comparison the maximum scour depth moved by as much as 50m between surveys at the Burgzand Noord wreck sites. Therefore, this observation highlights the stability at the Algerian. The location of the maximum scour depth was 9m further from the main cluster in both 2012 and 2013/04/22. For the former survey this is likely a result of the noisiness of the data over this area and for the latter, results from gaps in the data since the wreck was only insonfied from the south-east for this survey.

4.5.3.2 Bed-level change

From 2002 to 2006 a dramatic decrease in elevation (>1.4m in some places) is observed directly over the wreck of the Algerian (Figure 4.69a), this trend is then almost entirely reversed from 2006 to 2012 (Figure 4.69b). Therefore, this trend is likely the result of inaccuracies in the 2006 survey. There is, however, a very isolated area of the southwestern end of the wreck which does not recover in elevation from 2006 to 2012 and remains lowered throughout the rest of the time-series. It appears as though some of the structure at this end of the wreck is lost sometime during this 2002 to 2006 period. During this same period of time the northern most scour pit filled-in by 0.25m. It is possible
Figure 4.69: Bed-level change for the area surrounding the *Algerian* for a) August 2002 to 25th July 2006 b) 25th July 2006 to 2012 c) 24th Feb 2012 to 22nd April 2013 d) 22nd April 2013 to 25th April 2013 e) 25th April 2013 to 1st May 2013 f) 1st May 2013 to 26th March 2014 g) 26th March 2014 to 16th March 2015 h) 24th February 2012 to 16th March 2015 using a minimum detection threshold of ±0.2m.
that this complementary bed-level change could have sourced directly from the lost material at the south-western end.

On the whole, between almost all surveys, bed-level change is very close if not below the limit of detection and net bed-level change lies between ±0.1m. This is also reflected in the transects across the two scour pits which show no statistically significant change in elevation between years (Figure 4.70 and Figure 4.71). Where there is a difference between the lines it is generally attributable to horizontal errors in the surveys causing the transects to dissect part of the wreck structure, e.g., in Transect B for the 2002 survey.

Between some surveys it appears as though the detection threshold is too liberal, leading to the introduction of some data artefacts, such as the clear roll artefacts (survey track-aligned bands of bed-level loss adjacent to bed-level gain) between the 25th April and 1st May 2013 surveys (Figure 4.69e). There are also probable heave artefacts in the 22nd April 2013 survey which present themselves as strong parallel bands of bed-level gain and loss aligned with the survey track (which make them distinguishable from bedform migration which causes less uniform and not necessarily track-aligned banding).

Those areas where strong detectable bed-level change is observed relate to where bedforms have migrated between surveys creating strong bands of bed-level change. Bedforms to the north of the wreck appear more mobile than those to the south of the wreck (Figure 4.63). From Figure 4.63 it can be noted that there is no net migration of bedforms at the site. Some movement is seen between surveys; however, this does not occur in a single direction so is likely the migration back and forth over the ebb and flood tide.

As was highlighted in Section 4.5.1.4, were storm waves to have an impact on the site we would expect to see evidence of this between the 2013 and 2014 surveys when a greater than 1 in 10 year storm passed over the site. Over this period of time no areas around the wreck undergo any additional change; as expected this site is not subject to storm induced transport.

Figure 4.70: Elevation along transect A (the scour pit at the south-western end of the *Algerian*). Location of transect shown in Figure 4.67.
Chapter 4 Multibeam bathymetry time-series

4.5.4 Discussion

Whilst models suggest that the alignment of the wreck with the prevailing tidal flow should result in the formation of a singular downstream wake scour and limited deposition (Dix et al., 2007), the pattern of deposition at this site (a flow aligned ridge of deposition) is more comparable to a structure orientated perpendicular to the flow, suggesting that the width of the structure was sufficient to create two wake vortices with a region of reduced shear stress in-between.

There are two major processes which have resulted in observable bed-level change above the threshold for detection. Firstly, artefacts (predominately heave artefacts and incorrectly applied roll offsets) within the data. These have introduced fairly easily identifiable errors, but cannot be as easily removed without returning to the original data and performing further patch tests and better constraining the attitude sensor offsets. The second process is the migration of the medium subaqueous dunes, creating alternate banding of bed-level gain and loss alongside the wreck, particularly along the northern side of the wreck. It is clear that for this time-series the basic, spatially uniform, threshold for detection has resulted in the inclusion of data which are not likely real and are the result of errors in the collection and processing of these data. In the following chapter an attempt will be made at better constraining the spatially variable uncertainty of each survey in an effort to create DoD which more robustly describe the real change between the DEMs.

Despite the issues with using a spatially uniform threshold of detection the absence of any other strong coherent change highlights the wreck site’s morphological stability. There are several conditions at the site which may promote the observed stability at this site: i) the coarse grain nature of the bed material, preventing transport at low velocities, ii) the relatively week tidal asymmetry at the site reducing net transport of material, iii) the alignment of the wreck into the prevailing conditions, reducing the bluff edge exposed to transport, resulting in predominantly 3D flow about the structure and iv) its depth and location prevent even the most severe storms from acting on the site. As with the other
sites introduced within this chapter it is difficult, if not at all possible, to discern the relative importance of each of these factors in controlling the taphonomic processes at this wreck site.

4.6 Discussion

It has been shown in this chapter and Chapter 3 that time-series of MBES data capture both the structures created through scour and deposition processes (i.e. local and wake scour pits and ridges/areas of deposited material), as well as the processes themselves (bed-level gain, deposition; and bed-level loss, scouring) and the rate over which these processes occur.

Presently, making predictions of scour depth, extent and temporal evolution around submerged obstacles (cylinders, cuboids and piers etc.) still heavily relies on the use of empirical relationships predominantly derived through physical modelling (Lambkin et al., 2006; Saunders, 2004; Zhao et al., 2012) and latterly through a handful of numerical models (Huang et al., 2009; Zhao et al., 2010). These models have largely focused on the patterns of scour and to a much lesser extent, deposition, downstream of large, uniform, bluff structures (e.g. cuboids and monopiles). Dominant controls on the spatial patterning of scour and deposition include the obstacle’s geometry and its orientation relative to the prevailing flow (Saunders, 2004).

Almost all studies of scour around submerged bluff structures have focused on constraining local scour processes (characterised by its proximity to the obstacle and its steep sides), since this process is the primary cause of the destabilisation of structures (Whitehouse, 1998). Whilst local scour is observed at a number of the wreck sites presented here (Richard Montgomery, Scylla and to a lesser extent at the Algerian), wake scouring (characterised by its vast lateral extents and distinctive scour patterning; Saunders, 2004) was more predominant (in terms of its volume and spatial extent) at almost all the wreck sites (Richard Montgomery, Stirling Castle and the Burgzand Noord wrecks). The five wreck sites presented here provide the opportunity to study the environmental controls on the formation and evolution of the, presently poorly defined, processes of wake scour.

Furthermore, many of the modelled structures have been surface-piercing (e.g. monopiles and other foundations) and of similar geometry (e.g. cuboids and cylinders). Thus, few studies have focused on the impact of obstacle geometry on scour processes. As a result, no relationship has previously been identified to relate the wake scour dimensions to an object’s size or orientation. Since the wreck sites presented here display wake scour and a number of them (the Burgzand Noord sites and the Stirling Castle) change in their height above bed over the time-series, the controls of wreck geometry on wake scour extent can be examined.
Determining the extent to which the principles of scouring can be applied to wreck sites is a priority. Since, if wreck sites do behave as any other obstacle (e.g. cylinder, cuboids, piers and monopiles) on the seafloor, basic model derived relationships can be applied to these sites to both predict future, as well as constrain past, taphonomic processes. For example, if we know that the length of the scour pit relates to the obstacle height and we know the original obstacle (shipwreck) height, then we can make predictions as to the past extent of the scour pit. Considering scour pits have been shown to act as a trap for artefacts which have come loose from the main wreck superstructure (Quinn et al., 1997), this knowledge can then be utilised to target site investigations and tailor site management strategies.

In the following two sections the five wreck sites presented in this thesis are examined through relating their site conditions (structure geometry, hydrodynamics and geology) to their observed scour and depositional features. Following this, in Section 4.6.4, examples are given of how the understanding of wreck site taphonomy gained through this study can be applied.

4.6.1 Modern (20thC and later) wreck sites

Due to their modern construction materials and relatively recent dates of wrecking, the SS Richard Montgomery, Scylla and Algerian have similar preservation states and thus, bluffness to the modelled obstacles (mean heights of greater than 2.5m and peak heights of 6.5m or more). Observations from these three sites (Figure 4.72 a - c) strongly support the physical model result’s of Saunders (2004) (Figure 4.72 e - i). Those wrecks more closely aligned to the prevailing flow direction (the Algerian and Scylla) have reduced regions of scouring and deposition, in comparison to the near flow perpendicular SS Richard Montgomery, which has an extended, multi-lobed, wake scour pit.

Model derived relationships can also be used to predict the result of the tidal asymmetry at the Montgomery (the offset between the alignment of the flood and ebb flow direction results in the structure being aligned 79° to the flow during the flood tide and 65° to the flow during ebb tide). Saunders (2004) observed that obstacles orientated between 40 to 70° to the flow had scour lobe asymmetries of between 3 and 5, whereas, those oriented greater than 70° to the flow had scour lobe asymmetries of 1.5 or less. In near perfect agreement with these findings, there is an asymmetry ratio of 3.5 for the upstream lobes and 1.5 for the downstream lobes at the site of the Richard Montgomery.

The three more modern wrecks sites are comparably stable in terms of their large scale geomorphology. This is not necessarily a coincidence, since, for the long-term (multi-centurial) preservation of the historic wrecks and their recent exposure to enable them
Figure 4.72: Schematic of the pattern of scour and deposition with relation to obstacle orientation to flow for a) Algerian, b) Scylla, c) Richard Montgomery and e-i) proposed generalised patterns for an obstacle with a W:H of 5, after Saunders (2004), furthered by Dix et al. (2007) for an obstacle orientated e) 0°, f) 22.5°, g) 45°, h) 67.5° and i) 90° to the prevailing flow.
to be surveyed with MBES whilst on the surface, requires a very specific set of geomorphological conditions. Meanwhile, the more modern wrecks can still be found in environments not necessarily favourable towards the long-term preservation as: firstly, they are made of longer-lasting materials and secondly, they have not yet had time to degrade. Whilst the geomorphology may not enable the rapid burial of these wrecks, it does support multi-annual site stability in terms of the scour extent, maximum scour depth and maximum scour depth position. For example, despite having a scour pit that extends over 280m away from the wreck structure, the maximum scour depth at the Richard Montgomery remained within a 9m² area for all but two of the fourteen surveys (suggestions for the two anomalies were given in Section 3.3.3.3). Moreover, the net bed-level change at this site remained within the survey uncertainty (±0.3m) between each successive survey, i.e. there was no significant loss or gain in sediment over the site. Despite this large-scale stability, localised (over areas of <10’s metres) bed-level change over the range of ±3m was observed to occur. This demonstrates the importance of considering a range of spatial scales when studying the temporal variability at wreck sites.

4.6.2 Historic (17thC to 18thC) wreck sites

As a result of superstructure degradation and sediment deposition, the Stirling Castle and Burgzand Noord wrecks present a much less bluff surface to the flow than the more modern wrecks and can be described as wreck mounds. Dix et al. (2007, p.104) stated that discrepancies between their modelled relationships and field observations may have resulted from variable obstacle cross-sectional shape and/or longitudinal coherence (how dispersed the wreckage is). As a result we would expect these wrecks to fit less well with the empirical predictions.

Three key areas where the pattern of scour and deposition at the historic wrecks differ from the more modern wrecks, have been identified:

i. **Local scour and maximum scour depth position:** Local scouring at the Stirling Castle and the Burgzand Noord wrecks was extremely spatially limited and was not observed upstream of the wreck structures (Figure 4.52 and Figure 4.20). When present, local scouring was focused around upstanding isolated structures on the wreck (e.g. at the Stirling Castle around the ship’s rudder, Figure 4.52 a - c and to the north of BZN 3 in 2007, Figure 4.20). A result of the limited local scouring was that the maximum scour depth was often found within the wake scour pit, some distance from the wreck structure (e.g. more than 60m away from the Stirling Castle for the 2002 survey).

ii. **Definition of features:** Smaller scale features (few 10’s metres), such as local scouring and multi-lobed scour pits separated by a region of deposition, are only sometimes visible at these sites. There is evidence of a second scour pit close to
the wreck structure at BZN 3 for the years of 2004 and 2005, though not at the other three wrecks (BZN 4, 8 and 10) with similar alignments to the flow. By exception, downstream of the Stirling Castle, from 2002 to 2005, there was a region of deposition which, close to the wreck, created two separate areas of scour. However, these rapidly coalesced just 20 to 30m away from the wreck. Saunders (2004) also observed the coalescence of scour pits downstream of obstacles orientated 90° to the flow for some of his model runs, but didn’t comment on the cause. The coalescence of scour pits at other structures, such as gravity base foundations, has been observed and is termed ‘global’ or ‘dishpan’ scour (Whitehouse, 1998). Here, it is postulated that this occurs where wake vortices grow sufficient in size that their footprints overlap, and/or where the sediments cannot support steep angles, allowing the scour pit to grow in size as the its margins become less steep.

The lack of definition of sedimentary features also extends to the associated depositional features. For example, at the Stirling Castle and Burgzand Noord sites there was no natural break in slope between the areas of deposition and the wreck structure itself, preventing the identification of the wreck structure extent from the bathymetry alone.

iii. Spatial extent of wake scour: The length of the scour pits observed at these sites far exceeds (by almost a factor of 10) the lengths predicted through the relationship given by Saunders (2004), who suggested that the wake scour length is equal to 14 - 17 times the height of the obstacle. Using pioneering sidescan sonar techniques, Caston (1979) observed similar extensive corridors of scour (ranging from 75 to 1000m in length) downstream of a collection of 20 wrecks off the Kent and Essex coast. Off these 20 wrecks, 18 had observable ‘scour shadows’ which measured on average 238m. Since the average wreck height of these wrecks was estimated to be 8.7m, scour pit lengths were on average 27 times the height of the wreck. This value still falls short of the observations made in this chapter, but is more comparable than the estimates of Saunders (2004).

For the scour length observed at the Stirling Castle to fit with physical model results the wreck would have to stand 17m proud of the seabed. Since the wreck could have only ever stood 11m proud of the seabed (Whitewright, in review), even if the present wake scour pit was a relict of when the wreck was fully intact and fully exposed, the observed scouring is still longer than predicted using the modelled relationship by over 100m. Furthermore, the rapid response of the wake scouring to change in wreck height from 2002 to 2009 indicates that scour features from previous system states are not preserved. This suggests that the extended wake scour relates to the present site conditions rather than some former state.

Whilst the scour extent at these wreck sites is an order of magnitude greater than predicted, the trend in the relationship between obstacle height and wake scour length and
depth can still be tested for at these sites. Theory states that taller structures will have longer wake scours (Saunders, 2004). When the angle off attack was similar (e.g. comparing BZN 3 and 10, which have an angle of attack of 75° and 77°, respectively) the taller of the two wrecks (the BZN 3, which was taller on average by 0.7m) had a longer scour length (158m, in comparison to 103m for BZN 3), in agreement with the general trend observed by Saunders (2004).

Similarly, taller structures also have deeper local upstream and downstream scour pits (Zhao et al., 2010). Observed here, again through comparing BZN 3 and BZN 10. On average the scour depth is 0.2m deeper for the taller of the two wrecks (BZN 3), conforming with model observations.

Due to the large scale geomorphological processes resulting in a relative increase in wreck height at the Stirling Castle and a decrease in height at the Burgzand Noord wreck sites, these sites provide the unique opportunity to observe the impact of changing geometry (obstacle height) on the extent and depth of the wake scour features. It is anticipated that as the height of an obstacle is decreased that scour pit length should also decrease...
The relationship observed by Saunders (2004) projects that the relative decrease in height of the *Stirling Castle* from 3.3m in 2002 to 1.5m in 2009 should result in the relative decrease in scour length by 32m. The total scour length decreased by almost 200m over this period, a factor larger than predicted. In better agreement, the position of the maximum scour depth moved 35m closer to the wreck structure. Figure 4.73a shows that there is a strong positive correlation (n=22, r=0.81, p<0.01) between the wreck height and scour pit length. On average the wake scour pit length was 100 times the height of the wreck. Equally, Figure 4.73c shows that as the wreck increases/decreases in height and the wake scour pit also increase/decrease in length. Despite there being a strong relationship between increasing wreck height and scour pit length, Figure 4.73a shows that between some surveys the reverse trend was observed (e.g. BZN 11 from 2003 to 2004, BZN 10 from 2003 to 2004 and the *Stirling Castle* from 2005 to 2006.). This suggests that there is some short-scale (inter-annual) temporal variability and potentially that there can be lags between the change in wreck height and resultant scour pit adjustment.

Equally, Figure 4.73b shows that there is a strong positive correlation (n=22, r=0.86, p<0.01) between the wreck height and scour pit depth. As the height of the wreck increased the wake scour depth also increased, the inverse was also true (Figure 4.73d). Whilst the Burgzand Noord wreck fit well with a linear trend (maximum residual of just 0.19m), the *Stirling Castle* does not fit to this trend. Although the wreck decreased in height by 1.8m relative to the ambient bed-level, the scour pit depth at this site decreased by only 1.6m (less than the observed change at the BZN 3). This separation between the trends observed at the two sites could be a result of the differences in environmental conditions at the two sites (the BZN site has a finer sediment composition and maybe capable of supporting a larger range of scour pit depths; Melling, 2014).

The observed correlation between change in wreck height and both scour length and depth implies that those sites with a more stable wreck mound geometry will have a more stable scour pit. Not only did the maximum scour depth and scour length remain stable for those wrecks whose maximum height did not change significantly over the observation period (e.g. BZN 8, where the maximum wreck height remained within ±0.2m of the 2002 value), but also the position of the maximum scour depth remained within a much tighter radius (in the case of BZN 8, confined to a 3m radius). In comparison, at the BZN 3, which gained in height by over 0.4m over the time-series, the maximum scour depth moved by over 40m between surveys. Moreover, this stability was reflected in the range of bed-level change values observed in the area surrounding the wreck, which at BZN 8 remained consistently between −1 and 0.5m, whereas, BZN 3 underwent bed-level change in excess of ±2m.
4.6.3 Summary

To summarise the key points demonstrated in the previous two sections are:

- Predictions of scour and deposition extent made utilising physical and numerical model observations were upheld by the more modern wrecks (Richard Montgomery, Scylla and Algerian).

- More ‘wreck mound’ like sites (Burgzand Noord and Stirling Castle) had: extended corridors of scour; very limited areas of local scour; and less well defined scour pits and areas of deposition.

- Quantitative estimates of scour extent made using scour models are on the whole too conservative. The data presented here indicate that wake scour length is on the order of 100 times the obstacle height.

- Using MBES data alone, it is difficult to delineate the extent of scour and deposition. This is exasperated by the wide range of terminology used (e.g. local, wake, global, distal are all used to describe regions of scouring/sediment transport shadows, yet none of these terms have quantitative definitions).

- The large scale (kilometre) geomorphological instability observed at the historic wreck sites is not coincidental. These processes have enabled the long-term (multi-centurial) preservation of these wreck sites and the recent (over the past few decades) exposure on the surface enabling them to be surveyed using MBES systems.

- Those wreck sites with more stable geometries had more stable associated sedimentary features.

4.6.4 Implications

The agreement between the spatial patterning of scour and deposition observed by Saunders (2004) and observed at the five wreck sites presented here suggests that detailed object morphology is not a large control on the formation of scouring-associated vortices and that the simplification of these structures to cuboids when considering these processes is valid. Even in the case of the Scylla (aligned to the prevailing wave climate) the observed scouring was comparable to a cuboid aligned to a uni-directional (non-oscillatory) flow (Section 4.12). This indicates that when modelling the flow and resultant scour/deposition around an obstacle simplifications can even be made with regards to the hydrodynamic conditions at the site. The ability to generalise the hydrodynamics at the wreck site is advantageous to the study of processes around wreck sites where the Metocean conditions cannot be well constrained, e.g. more remote locations where few/no wave buoy or current meters have been deployed. From the observations in this
chapter it appears that, in terms of the hydrodynamics, the minimum requirement to describe the general spatial extent of the scour and the deposition at a wreck site is: i) the prevailing flow direction relative to the object orientation, ii) the strength of the flow asymmetry and iii) whether or not flow is sufficient for transport (i.e. whether the site is clear water or live-bed). The first two pieces of information can often be estimated using tidal diamond data (at sites where the tidal current is predominant) or a wave buoy time-series (at sites where the oscillatory motion is predominant) and the third can be assessed using MBES data through assessing the presence or absence of bedforms for the surrounding seafloor. From this information alone a basic assessment of the number of scour pits, scour pit length and the position of the areas of scour and deposition relative to the wreck can be made.

Furthermore, many of these relationships can be used to both retrieve previous and predict future conditions. For example, we know that in 1979 the structure of the *Stirling Castle* stood 6 - 8m proud of the seafloor (Lyon, 1980). Using the observed relationship (scour pit length is approximately 100H) would give a maximum scour length of greater than 600m. McNinch *et al.* (2006) have shown that loose and transportable artefacts often collect within the confines of the scour pit and so, it is possible that remains of the *Stirling Castle* are to be found up to 660m downstream of the structure in the now filled, relic, scour pit. The same principle was used by Quinn *et al.* (1997) and Missiaen *et al.* (2012), both of whom were able to observe the bounds of a relic scour pit using geophysical techniques. This understanding could be used to better focus archaeological investigations and to tailor site protection (e.g. through the modification of exclusion zones (Dix *et al.*, 2007), to ensure the full extent of the wreck site is protected).

An understanding of scour and deposition processes can also be used to identify those sediment deposits which are more or less likely to yield archaeological material transported from the wreck site. For example, both the BZN 3 and *Stirling Castle* wrecks have a wedge of deposited material on their upstream face. This material is likely to have accumulated on the stoss side of the wreck as a result of the obstruction posed by the wreck to ambient net sediment transport (Dix *et al.*, 2007). Therefore this material has come from upstream of the wreck and is not material which has been excavated through scouring. As a result it is less likely to contain artefacts removed from the wreck and would not necessarily be worth archaeological investigation or management.

Wreck sites with large scour marks have often been assumed to be more dynamic and temporally unstable (Lawrence and Bates, 2001). In this chapter and the previous, it has been shown that these marks can form rapidly (e.g. approximately 50% of the scouring at the *Richard Montgomery* was observed just 7 years after wrecking) or result from a singular event (the scouring observed around the wreck of the *Scylla* occurred after a winter where a 1 in 8 year storm passed over the site) and remain stable, especially as those sites where there is no active process to infill the scour pit, e.g. those sites with clear-water conditions such as the *Richard Montgomery* and *Scylla*, on scales of years to
decades. Following the 1 in 8 year storm at the Scylla the bed elevation underwent no discernible change over the next two years. Equally, the inter-annual net bed-level change at the Richard Montgomery remained within the LoD$_{min}$ of ±0.3m. Additionally, it was shown that those wrecks where ambient conditions are insufficient for extensive scouring to develop (e.g. the Algerian) are also capable of supporting stability on these time-scales (net bed-level change < ±0.3m between surveys). Since carrying out observations at these sites is costly, an understanding of the time-scale over which a wreck site can remain stable is of use for the management of such sites. By projecting the scales over which change may occur site monitoring programmes can be better tailored to reduce the number of surveys and thus, the cost of conserving such sites.

The findings of this study highlight that importance of considering the wider impacts of site management. For example, the application of physical protection (polypropylene matting) at BZN 3 resulted in the destabilisation of the area downstream (extending at least 175m downstream) of the wreck. Since there did not appear to be any further wrecks in the area immediately downstream of BZN 3 this did not result in the disturbance of any other deposits. However, were BZN 8 to undergo the same level of scouring as BZN 3 then this could easily extent as far as the neighbouring BZN 10, located just 150m downstream. This example shows the importance of taking into consideration the impact that physical protection can have on the system, which could theoretically be forecasted using an understanding of basic scour principles.

Whilst basic scour principles are upheld at these five wreck sites, other environmental forces are still of importance and have been observed to supersede scour/depositional processes. For example, at the site of the Stirling Castle large-scale geomorphological controls (multi-kilometre bank migration) have in the past (in the late 1970’s) uncovered the wreck and more recently (from 2002 to 2009) begun to rebury the wreck. Without an appreciation for the bank-scale spatial processes of the Goodwin Sands and/or with only a short (less than decadal) time-series of the Stirling Castle one would be unable to forecast or have an understanding for the past exposure and/or burial of this dynamic site. This could potentially lead the user to invest management into an archaeological site which in a few years time could once again become buried and thus no longer in need of physical protection. Clearly, an appreciation for long-term and/or large scale (as the two are inextricably linked) geomorphological processes are important to the heritage management of shipwreck sites.

4.6.5 Limitations

A consideration and often a constraint, on the effective quantification of bed-level change at each of the wreck sites, is the estimation of the elevation uncertainty of each DEM surface. In this chapter, spatially uniform thresholds of detection were employed at each
of the sites, ranging from ±0.2m to ±0.3m. These were often overly conservative in areas where the bed-level is well constrained (e.g. flat and featureless areas of the seafloor) and resulted in the exclusion of change which is probably real and detectable, e.g. at the *Scylla* between the 2011 and 2013 survey and between the two 2013 surveys, where a threshold of ±0.28m was proposed based upon a-priori TPU estimates. Equally, these thresholds have been deemed to be too liberal where depth artefacts dominate the bed-level change, e.g. at the wreck of the *Algerian*. Furthermore, the choice of which area of the seafloor to use as the ‘ambient’ area when quantifying the LoD$_{\text{min}}$ threshold makes this method moderately subjective and as a result, less vigorous. Clearly, a more robust methodology is required to evaluate the elevation uncertainty of MBES DEMs. Whilst there are insufficient data (the minimum requirement is the original point spacing file) to allow for analysis of the spatially variable elevation uncertainty for most of the sites through Geomorphic Change Detection (GCD) techniques (SS *Richard Montgomery*, *Stirling Castle*, *Scylla* and Burgzand Noord), the time-series of the *Algerian* is complete enough to allow for further examination. This will be performed in the following chapter and the implications of this analysis will be considered in regards to the other four wreck sites.
As discussed in Section 2.1.5.9 of Chapter 2, when comparing two Digital Elevation Model (DEM)s through a DEM of Difference (DoD) the uncertainty of each surface must be taken into consideration in order to determine whether or not the observed change is statistically significant. In Chapters 3 and 4 spatially uniform thresholds of detection (minimum level of detection threshold; LoD$_{\text{min}}$) were used. These thresholds were set based upon the differences between DEM surfaces where no or limited change was anticipated (e.g. areas of bedrock or anthropogenic structures). In reality, the uncertainty of the DEM is not fixed and will vary spatially. Therefore, the use of a fixed, spatially uniform minimum level of detection threshold (LoD$_{\text{min}}$) will result in the over conservative removal of data where the vertical uncertainty is small (e.g. flat areas with a high survey point density) and a liberal accommodation of data where vertical uncertainty is high (e.g. areas with large slopes and low survey point density) (Wheaton et al., 2010).

One potential methodology for assessing the spatially variable Total Propagated Uncertainty (TPU) was described in Chapter 2, Section 2.1.5.1. Here, the manufacturers’ estimates of each instrument’s uncertainty are combined, giving a TPU for each depth sounding. There are two methods for deriving the TPU for the DEM within CARIS: the mean and the Combined Uncertainty Bathymetric Estimator (CUBE) method. The differences in gridding methods results in an almost undetectable difference between these two surfaces (e.g. for the 2014 Algerian surface there was a mean difference between the two surfaces of $<0.001\text{m}$ and a maximum difference of $0.003\text{m}$). Therefore, the CUBE methodology (used by Schimel et al., 2015) is comparable to the mean methodology used in this chapter. Schimel et al. (2015) observed that the spatially variable TPU surface gave better results (smaller and more realistic, confidence intervals) than using a fixed, LoD$_{\text{min}}$, uncertainty value. Whilst this methodology can be applied to data where either the TPU surface is provided or sufficient data (raw Multibeam Echo-Sounder (MBES) survey lines and estimates of the uncertainty of each instrument) are provided to create a TPU surface, this method cannot be applied to legacy data where only the processed
bathymetry file is available. Although Schimel et al. (2015) aimed to close (and did succeed at the very least in reducing) the methodological gap between the fields of marine and fluvial geomorphology (where in the latter the use of spatially variable uncertainty surfaces is already commonplace), there is still one step further which can be taken to close this gap entirely, the application of Geomorphic Change Detection (GCD) techniques.

GCD methods exploit the understanding that DEM vertical uncertainty exhibits patterns in its spatial variability that are coherent and predictable. Wheaton et al. (2010) observed that where DEM surfaces had higher slope and lower point density the elevation uncertainty was greater and that where bed-level change was real between surfaces this tended to occur over coherent areas, rather than isolated small patches. Utilising this knowledge, Wheaton et al. (2010) developed an ArcMap package, GCD, which estimates DEM vertical uncertainty and DoD probability through two different methods: i) spatially variable uncertainty quantification and ii) spatially coherent units. At fluvial sites the uni-directional flow forces the progression of geomorphological features to occur in one direction, creating coherent areas of bed-level change. On the contrary, exemplified best by the Richard Montgomery MBES time-series, the change at marine sites does not on the whole occur coherently. As a result, in this chapter the focus shall be on using the former method. Details of both methods are given in Wheaton (2008) and Wheaton et al. (2010). By utilising either one or both of these methods the GCD software produces DoD which have been demonstrated to be more plausible and physically meaningful, than those generated using a fixed threshold, i.e. in those areas where anecdotal field evidence suggested there was real and coherent change the GCD methodology recovered the change.

Ideally, a simple monotonic relationship would be identified between the DEM surface properties and the uncertainty. However, Wheaton (2008) observed that the DEM properties (e.g. slope and point density) did not vary linearly with the vertical uncertainty. As a result a simple deterministic model could not be used to relate the two. Instead, a Fuzzy Inference System (FIS) is used to relate the surface properties to the uncertainty.

Though originally developed for use with terrestrial Real Time Kinematic (RTK) Global Positioning System (GPS) and total station data, GCD methods have since been applied to fluvial MBES data (Hensleigh, 2014). Further modification of these methods is required before the GCD package can be used with marine MBES and these are described within this chapter.

An essential requirement to calibrate the GCD package (necessary each time a new survey set-up is used) is the raw point spacing x/y/z file. This point file must also be of sufficient point density to provide a large number of coincident points. Using the Algerian data 150 points was deemed sufficient to capture the full range of slope, roughness
and z error values (Figure 5.1). Similarly, using the Algerian and BZN 11 datasets a relationship between the point density and number of coincident points was established (Figure 5.2). As the sampling density increased the number of coincident points increased logarithmically. Using this relationship, knowing the required number of coincident points and either the planned survey area or point density, the other attribute can be estimated. For example, if you had an average point density of 10 points per square metre, and you required 150 coincident points to generate your FIS, you would have on average 0.003 coincident points per square metre and would require a survey area of at least 50,000m².

Since raw point files are required for the GCD methodology and considering the MBES time-series presented in this thesis, these techniques can only be applied to the Algerian and the BZN 11 surveys. As the original line files have been collated for the Algerian time-series (unlike the BZN 11 time-series), allowing for the generation of a-priori TPU surfaces, this MBES series is used here to demonstrate the usefulness of GCD techniques to estimate spatially variable DEM uncertainty.

### 5.1 Geomorphic Change Detection methods

The GCD package has been used for a wide range of data types: LiDAR; colour bathymetry, Moretto et al. (2014); Terrestrial laser scanner (TLS), Bangen et al. (2014); GPS station; fluvial MBES, Hensleigh (2014); historical charts, James et al. (2012); and even laboratory based structure-from-motion topography, Kasprak et al. (2014). The tool has also been used to assess geomorphic change for a range of different environments, including to
assess the effects of flooding (Croke et al., 2013), debris flow modelling across an alluvial fan (Wasklewicz and Scheinert, 2015) and even centimetric elevation change of sediment within a water flume tank (Kasprak et al., 2014). For the most part applications have been terrestrial and fluvial based, highlighting the lag between the fields of terrestrial and marine geomorphology, also noted by Schimel et al. (2015). This is the first study to apply these methods to marine MBES data. It is anticipated that the reduced range in seabed properties (e.g. slope and roughness), resulting from the lack of bank, bar and channel features and the impact of the seafloor depth (the increased depth in comparison to fluvial environments will decrease the point density and so the number of coincident points), will make it more difficult to create a robust model for the GCD analysis. Submerged anthropogenic structures (in this case a shipwreck) and their associated scour pits are likely to produce far greater surface roughness and slope values than ambient areas of seafloor. As a result, the Algerian time-series will provide the opportunity to test the effectiveness of GCD methods over a range of bathymetric complexities than a featureless area of seafloor.

The main workflow of the GCD application is depicted in Figure 5.3. There are five different pathways through which a DoD can be taken through the GCD software (Wheaton, 2008). The majority of the work flow is fairly self-explanatory and involves little user input (conversion to space delimited file, conversion of space delimited file to point file, conversion from point file to Triangulated Irregular Network (TIN), conversion from TIN to raster, creation of slope, point density and roughness surfaces etc.). Therefore, the methods for these processes are not given here. However, the methodology for selecting

![Figure 5.2: Relationship between point density and the number of coincident point per area, determined using average point density and number of coincident points for the Algerian (blue) and BZN 11 (red) surveys.](image-url)
Figure 5.3: Workflow for Wheaton and colleagues’ Geomorphic Change Detection plugin in ArcMap.
the optimal gridding resolution is given in the following section, along with descriptions of the FIS model inputs (roughness, slope and point density) and the variable used to train the model (coincident point z error). Before finally, a description of the methods employed to develop a rule set for the FIS is given.

5.1.1 Sampling and grid resolution

The first step, before performing any GCD analysis, is to determine both the sampling resolution of the input MBES and the appropriate grid resolution to perform the analysis at. The choice of grid resolution is critical, as too fine a resolution will cause an increased burden on the computational analysis (tools will run slower, or not at all), whereas, too coarse a resolution will result in the loss of detail (small spatial scale change). A simple way to determine the sampling resolution is to use the ArcMap Average Nearest Neighbour tool which iteratively calculates the average distance between the nearest neighbour points. This method does not account for the difference in sampling resolution between the interior angles of the swath and the exterior angles. Where depth, beam angle, slope and beam width are known the across-track and along-track footprint sizes can be determined, which will give the full range of attainable sampling resolutions. However, this second method does not account for repeat survey passes and the resultant overlap of swaths. Therefore, as performed by Hensleigh (2014), the optimal raster resolution will be found using the Average Nearest Neighbour tool.

The value provided by the Average Nearest Neighbour tool gives the absolute minimum cell resolution that is possible without introducing unnecessary interpolation. During the GCD analysis, products, specifically surface roughness, require more than one point per cell to be calculated (the roughness tool requires a minimum of 4 points per cell). As a result, a coarser resolution (approximately twice as coarse) than the absolute minimum cell resolution is required.

As the minimum mean point spacing was 0.25m for the Algerian time-series (Table 4.22) and the minimum required number of points per cell to calculated roughness is 4, a grid spacing of 0.5m should be sufficient. However, due to the variability in point spacing, a cell size of 0.5m resulted in 71% of cells having fewer than 4 soundings for the 2013/04/22 survey (the survey with the lowest average sounding density). Instead a 1m cell size is used during the GCD analysis. This resulted in an average point density for each one metre raster cell of 15 points/m\(^2\) and a coverage of 98% for the 2013/04/22 survey (i.e. 98% of the cells at a resolution of 1m had 4 or more depth soundings).

5.1.2 Potential model inputs

In order to estimate the spatially variable uncertainty, surfaces derived from the DEM which also exhibit the same patterns as the uncertainty are required. In this section three
surfaces which could potentially be used as inputs for the GCD model are described: roughness, slope and point density (Figure 5.4).

Figure 5.4: Surfaces of a) bathymetry (with survey lines and spatial extent of subplots outlined in red), b) roughness, c) slope, d) point density, e) TPU and f) coincident point vertical uncertainty for the 2015 survey of the Algerian.

5.1.2.1 Roughness

Roughness is a descriptor of the spread of elevation values within a chosen area (raster cell) (Figure 5.5). Roughness can be heavily skewed by local surface slope, as a result this local slope has to be removed (detrended) before statistics on the roughness can be performed. Values of roughness are generated using the Topographic Point Cloud Analysis.
Toolkit (ToPCAT) roughness tool, which calculates the detrended standard deviation of a decimated point cloud (Rychkov et al., 2012). The detrended standard deviation describes the variability of elevation values over a certain area. A depth cell which has been generated using points with large variability between them will have a larger associated uncertainty, the inverse is also true (Figure 5.6a).

The choice of cell resolution when calculating the roughness will affect the features described by the roughness surface. For example, when the cell resolution is small (less than half the wavelength of any bedforms present) then the roughness will describe both the grain size distribution and potentially, any data artefacts. For example, the increased uncertainty of the outer beams is captured in Figure 5.7a. When the cell resolution is greater than half the wavelength of any bedforms present then the bedform slope can no longer be detrended and the roughness now describes the height of the bedforms (Figure 5.7b).

As the cell size increases the features which are no longer detrended and are then considered roughness, increase in size. As a result the roughness increases with cell size. At the Burgzand 11 site since the survey area is small there is only one type of bedform and so, roughness increases near linearly with cell size (Figure 5.8a). Whilst the overall trend in increasing roughness with cell size is observed at the Algerian (Figure 5.8b), there are jumps in the mean roughness, likely corresponding to where differing morphological features are captured as cell size increases. A result of the change in roughness with cell
Figure 5.6: Schematic of the impact of seafloor a) roughness and b) slope on depth measurement uncertainty. Where $z_0$ indicates the target depth for which the x and y positions will be reported and $z_1$ indicates the likely observed depth for that footprint. The difference between the two depths represents the depth uncertainty. Figure adapted from Hensleigh (2014).

Figure 5.7: Impact of cell resolution on roughness. Roughness surface for the 2014 Algerian survey at a) 1m and b) 10m cell resolution.

size is that any FIS developed is specific to a cell size. Therefore, all analyses must be performed at the same resolution.

5.1.2.2 Slope

Through calculating the rate of maximum change in depth from each cell, the slope of the seafloor describes the topographic complexity of the area. Areas of high slope will result in less accurate depth readings since the return will be skewed towards the shallowest
depth within the area of the insonified seafloor (Figure 5.6b). Like roughness, increasing the cell size also increases the value of the slope. Thus a FIS trained with data at a certain cell size can only be used with data at the same cell size.

5.1.2.3 Point density

Those raster cells which have fewer depth readings within them, i.e. a lower point density, have to place more reliance on a smaller number of points to estimate the elevation. Therefore, the uncertainty of these cells will be higher. Unlike slope and roughness, which are influenced directly by the properties of the seafloor, the point density is purely a result of the survey method. For example, the point density for the 2015 Algerian survey is greatest over the wreck (Figure 5.4), the higher point density should act to lower the uncertainty of DEM cells over the wreck.

5.1.3 Coincident points

In order to calibrate the FIS rule system an empirically derived value of the vertical uncertainty of the DEM is required. In this analysis the difference between coincident points is used. As discussed in Chapter 2 Section 2.1.5.8 Method 8, coincident points are where two depth soundings have the same x and y coordinate. By comparing the elevation of two coincident points an estimation of the vertical uncertainty at the sounding’s location can be made.

Three processes have been identified which result in depth soundings having coincident positions: i) during a single profile two adjacent beams can have the same footprint, ii) two adjacent profiles can overlap, e.g. when the vessel is near stationary or pitching back and forth due to wave action and iii) two non-adjacent profiles can overlap, e.g. when the survey track covers the same ground twice. Each one of these processes will result
in slightly different z errors. The first will likely be where the x and y of the sounding is inaccurate, i.e. two different areas of the seafloor have been sounded. This will likely result in a large z error. The second method will give a good approximation of instrument uncertainty, since all other variables (sound velocity, tidal elevation etc.) will have remain the same over the very small time space between the two soundings. The final method will give an estimation of the impact of both instrument uncertainty and time varying uncertainties (the size of which will be dependent on how long the time spacing is between the two repeat soundings and how temporally variable the errors are). This type of coincident point will also be influenced by bed-level change on short time-scales (e.g. bedform migration).

5.1.4 Fuzzy Inference System

As mentioned previously Wheaton’s GCD methodology relies on the strong and predictable spatial bias in elevation uncertainty, e.g. areas that have high slope values, low point density and high surface roughness, have very high elevation uncertainty and inversely, areas that have low slope, high point density and low surface roughness have a low elevation uncertainty. A deterministic model from these relationships cannot be unambiguously constructed since no simple monotonic relationship exists between the spatially variable properties and elevation uncertainty (Wheaton et al., 2010). Instead, a more heuristic approach, Fuzzy set theory, is used.

FIS is a method of putting imprecise and complex concepts in numerical form. The rule definition for the FIS linguistically relates the inputs (e.g. slope, roughness, point density, point quality etc.) to a single adjective for the output (in this case vertical uncertainty). For example, a cell with a low point density and a high slope would be expected to have a high elevation uncertainty. The number of inputs can vary, but is typically two or three. The output membership function is then defuzzified using its centroid, so that a crisp (single) value of uncertainty is given. The output of elevation uncertainty is calibrated to a range of empirically determined values (e.g. the elevation error between coincident points). The creation and calibration of the FIS is performed here through Matlab’s Fuzzy Logic Toolbox.

An example rule system is shown in Figure 5.9 and Table 5.1. This has been trained using the surveys from the wreck of the Algerian. The rule system here is weighted towards roughness, e.g. a high roughness and a medium slope give a extreme uncertainty class, whereas, a medium roughness and a high slope give just a high uncertainty class. This is because, as will be shown in Section 5.2.1, the relationship between uncertainty and roughness is stronger than the relationship between uncertainty and slope.
Figure 5.9: 2-rule a) roughness and b) slope, FIS to determine c) elevation uncertainty, for the Algerian MBES time-series. Where mf is the membership function of the input/output.
Table 5.1: FIS rule system for the Algerian time-series.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Roughness</th>
<th>Slope</th>
<th>Uncertainty Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>4</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>5</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>6</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>8</td>
<td>High</td>
<td>Medium</td>
<td>Extreme</td>
</tr>
<tr>
<td>9</td>
<td>High</td>
<td>High</td>
<td>Extreme</td>
</tr>
</tbody>
</table>

In this analysis a 9-rule, 2-input, Mamandi-type (the most commonly used Fuzzy Inference method) FIS is used. The same fuzzy operation, rule implication, aggregation and defuzzification methods are used here as were used by Wheaton et al. (2010).

Once created and calibrated the FIS rule system is applied on a cell by cell basis to compute an uncertainty value. This is then repeated for each survey (with a new rule system if necessary, i.e. if a different survey setup is used). Once complete, the uncertainties of each cell from survey 1 and survey 2 are combined using simple error propagation theory (Equation 2.2).

A probability map of the DoD is then created between the two surveys, where only those cells with a value greater than the uncertainty are kept. To further increase the robustness of the DoD a probabilistic threshold can be used based on a confidence interval (generally set to 0.95, i.e. a 95% confidence level).

5.2 Geomorphic Change Detection for the Algerian time-series

In this section an assessment is made of the effectiveness of using the spatially variable surfaces of roughness, point density and slope to estimate spatially variable uncertainty. An FIS model is developed based upon this assessment and then applied through the GCD package. The resultant thresholded DoD are compared to the spatially uniformly thresholded DoD and to DoDs thresholded using a-priori estimates of TPU.
5.2.1 Fuzzy Inference System development and application

The number of coincident points for each survey is given in Table 5.2. Those years with higher point densities (Table 4.22) on the whole have a larger number of coincident points. The mean difference between elevations of coincident points is on average 0.09m. Though the average difference is far higher (on average 0.30m) for the 2012 survey. As the same MBES system was used for this survey as for the years of 2013 to 2014 then a change in survey equipment cannot be the cause of the elevated z error. It could be that the population size (just 760 coincident points in comparison to other years which had on average 5900 points) is not sufficient to be representative of the true depth uncertainty or that survey conditions may have been less favourable during the 2012 survey (the range in heave values for 2012 was twice that of any other survey; Table 4.23). Though, perhaps most likely, this offset between coincident points results from using the Portsmouth tide gauge data, which was only used for this year. As mentioned in Section 4.5.2 and shown in Figure 4.65, a 0.3m difference is observed between the Calshot and Portsmouth tide gauge at high water, so this could easily account for the 0.30m difference between coincident points.

Table 5.2: Number of coincident points for each MBES survey, the average difference between elevation values and the 95% confidence interval for the z error.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total number of coincident points</th>
<th>Number of coincident points excluding same profile points</th>
<th>Mean difference between coincident points (m)</th>
<th>Standard deviation difference between coincident points (m)</th>
<th>95% confidence range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012/02/24</td>
<td>760</td>
<td>669</td>
<td>0.26</td>
<td>0.30</td>
<td>±1.06</td>
</tr>
<tr>
<td>2013/04/22</td>
<td>2179</td>
<td>1886</td>
<td>0.04</td>
<td>0.11</td>
<td>±0.31</td>
</tr>
<tr>
<td>2013/04/25</td>
<td>12188</td>
<td>12081</td>
<td>0.02</td>
<td>0.13</td>
<td>±0.40</td>
</tr>
<tr>
<td>2013/05/01</td>
<td>2432</td>
<td>2382</td>
<td>0.08</td>
<td>0.11</td>
<td>±0.33</td>
</tr>
<tr>
<td>2014/03/26</td>
<td>6958</td>
<td>4844</td>
<td>0.11</td>
<td>0.15</td>
<td>±0.46</td>
</tr>
<tr>
<td>2015/03/16</td>
<td>5752</td>
<td>5671</td>
<td>0.05</td>
<td>0.15</td>
<td>±0.36</td>
</tr>
</tbody>
</table>

The values in Table 5.3 describe the propagation of uncertainties, using Equation 2.2, when comparing two surveys. On average these give a $\text{LoD}_{\text{min}}$ of ±0.2m, in agreement with the ±0.2m threshold used in the analysis in Chapter 4.

The mean coincident point uncertainties for the Algerian MBES data are on average twice as large as those observed for the BZN 11 surveys (Table 4.14). Both time-series used a RESON 8125 system and so the main difference between the two is the navigation system used: RTK-GPS for the BZN 11 surveys and Differential GPS (DGPS) for the Algerian time-series. It is likely that the larger vertical uncertainties associated with the
Table 5.3: Propagated error based on standard deviation difference between coincident points.

<table>
<thead>
<tr>
<th>DoD</th>
<th>Propagated error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012/02/24 - 2013/04/22</td>
<td>±0.32</td>
</tr>
<tr>
<td>2013/04/22 - 2013/04/25</td>
<td>±0.17</td>
</tr>
<tr>
<td>2013/04/25 - 2013/05/01</td>
<td>±0.17</td>
</tr>
<tr>
<td>2013/05/01 - 2014/03/26</td>
<td>±0.18</td>
</tr>
<tr>
<td>2014/03/26 - 2015/03/16</td>
<td>±0.21</td>
</tr>
</tbody>
</table>

*Algerian* time-series resulted from the use of a less accurate navigation system ([Ernstsen et al., 2006a](#)).

As described in Section 5.1.3 the different methods by which depth readings can have coincident values will result in differences in the observed elevation error. Initially all coincident points were utilised in the FIS rule system development. However, this resulted in a strong peak in elevation difference of approximately 0.1m (Figure 5.10a). It was observed that these coincident points represented those caused by the first method (when during a single profile two adjacent beams have the same footprint). As these coincident points did not vary in elevation difference with the other properties (slope, roughness, point density) these points (on average 10% of the coincident points) were excluded from any further analysis (Figure 5.10b).

![Figure 5.10](#) Histogram of elevation differences between coincident points a) before and b) after, same-profile coincident points are removed. Data from the 22/04/2013 survey.

With the exception of two surveys the resultant distribution of elevation uncertainties (once coincident points from the same profile had been removed) is relatively even, decreasing frequency towards higher uncertainty values (Figure 5.11). The 01/05/2013 survey (Figure 5.11d) has a second peak at 0.1m. This appears to result from coincident points located in the upper three tracks which do not overlap and are therefore a result of the second method described in Section 5.1.3. The consistency of these errors suggests they may not be real and possibly highlights that coincident points caused by this method should also be excluded from further analysis. However, since for this survey the number of coincident points is already low (2382) these points were utilised in the analysis. The 2012 survey (Figure 5.11a) has an entirely different distribution, with an
almost even spread of values from 0m up to 1m. As mentioned previously this could be a result of the tidal elevation record used to correct this survey.

Figure 5.11: Histogram of elevation differences between coincident points for the a) 2012 b) 2013/04/22 c) 2013/04/25 d) 2013/05/01 e) 2014 and f) 2015 surveys.

In Figure 5.12 the location of the resultant coincident points and their associated elevation uncertainty are shown. The majority of the coincident points are observed where two swaths overlap. As a result these values represent the elevation difference between outer beam values, which tend to have larger associated uncertainties (Whittaker et al., 2011). Theoretically this skew towards outer beam coincident points could be removed by resampling the data evenly across the whole range of beams. However, with the style of survey used for the *Algerian* site (with very minimal swath overlap) this was not possible.

Surfaces of slope, point density and roughness are shown in Figure 5.13, Figure 5.14 and Figure 5.15. Both roughness and slope increase over areas of topographic complexity, e.g. directly over the wreck structure. Roughness is considerably higher towards the edges of the swaths in agreement with the literature (Maleika et al., 2011).

Point density is relatively even across the swath and only increases noticeably where two swaths overlap. As mentioned previously, this tends to be where outer beams overlap (with the exception of the 2015 survey where the non-traditional survey pattern resulted
Figure 5.12: Distribution and elevation uncertainty ($\delta z$) of coincident points for the b) 2012 c) 2013/04/22 d) 2013/04/25 e) 2013/05/01 d) 2014 and g) 2015 surveys of the Algerian. The location of b - g shown in a.
in relatively few outer beams overlapping). Since outer beams have higher uncertainties associated with their depth values then areas of high point density are likely to correlate to areas of higher vertical uncertainty, the opposite of the theoretical relationship between point density and z error.

Table 5.4: Strength of correlation between z error (from coincident points) and roughness, slope and point density, for each survey.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Roughness</th>
<th></th>
<th>Slope</th>
<th></th>
<th>Point density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
<td>r</td>
<td>p</td>
<td>r</td>
</tr>
<tr>
<td>2012/02/24</td>
<td>0.53</td>
<td>&lt; 0.01</td>
<td>0.13</td>
<td>0.31</td>
<td>0.04</td>
</tr>
<tr>
<td>2013/04/22</td>
<td>0.61</td>
<td>&lt; 0.01</td>
<td>0.27</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>2013/04/25</td>
<td>0.51</td>
<td>&lt; 0.01</td>
<td>−0.05</td>
<td>0.45</td>
<td>−0.38</td>
</tr>
<tr>
<td>2013/05/01</td>
<td>0.55</td>
<td>&lt; 0.01</td>
<td>0.21</td>
<td>0.15</td>
<td>−0.07</td>
</tr>
<tr>
<td>2014/03/26</td>
<td>0.54</td>
<td>&lt; 0.01</td>
<td>0.18</td>
<td>0.22</td>
<td>0.01</td>
</tr>
<tr>
<td>2015/03/16</td>
<td>0.59</td>
<td>&lt; 0.01</td>
<td>0.44</td>
<td>&lt; 0.01</td>
<td>−0.17</td>
</tr>
</tbody>
</table>

From Figure 5.16 it can be seen that as slope and roughness increase so does the difference in elevation between the coincident points, following the predicted trend. In order to determine the strength of the relationship between the slope, roughness or point density and the elevation uncertainty the correlation coefficient between the two variables were calculated for each survey. As the strength of the relationship is influenced by the size of the population used, a 100 value subsample was used to determine the correlation coefficients. This was then repeated 100 times and the average was taken. These values are given in Table 5.4. From this it can be seen that roughness is strongly correlated with the elevation error. Slope and point density have a much weaker or no correlation with uncertainty. Though, visually (using Figure 5.12 to Figure 5.14) slope does appear to be higher where uncertainty is higher (e.g. over the wreck) and lower were uncertainty is lower (e.g. to the north of the site). Whereas, the spatial distribution of point density appears to be purely related to the survey strategy of any given year. As a result a 2-rule FIS is developed using surface roughness and slope. Despite not including point density within the FIS, point density will later be incorporated indirectly through the inclusion of an interpolation error surface.

An initial FIS rule system was created using the MATLAB fuzzy logic toolbox. The effectiveness of the FIS model at estimating the vertical uncertainty of a depth reading was determined by keeping a subset of the original coincident points separate from the initial build of the FIS model and then iteratively modifying the values of slope and roughness of these test points into the FIS model and comparing the output to the given elevation uncertainty from the coincident elevations of the point. The smaller the total residual of all the values and their modelled outputs, the better the model was performing. In this way the model was fine tuned. The final chosen values for the FIS system are displayed in Figure 5.9. Both roughness and slope were split into three categories with overlapping
Figure 5.13: Surfaces of slope for the a) 2012 b) 2013/04/22 c) 2013/04/25 d) 2013/05/01 e) 2014 and f) 2015 surveys of the Algerian. Same spatial limits as Figure 5.12.
Figure 5.14: Surfaces of point density for the a) 2012 b) 2013/04/22 c) 2013/04/25 d) 2013/05/01 e) 2014 and f) 2015 surveys of the Al\`erian. Same spatial limits as Figure 5.12.
Figure 5.15: Surfaces of roughness for the a) 2012 b) 2013/04/22 c) 2013/04/25 d) 2013/05/01 e) 2014 and f) 2015 surveys of the Algerian. Same spatial limits as Figure 5.12.
boundaries: low (0.00 - 0.10m and 0 to 8°), medium (0.05 to 0.40m and 2 to 25°) and high (0.20 to 1.00m and 15 to 50°) (Figure 5.9a-b). Whereas, elevation uncertainty was classified into four overlapping categories low (0.00 - 0.10m), medium (0.08 - 0.20m), high (0.14 - 0.35m), and extreme (0.32 - 0.72m) membership functions (Figure 5.9c). The resultant surfaces are shown in Figure 5.17.

In good agreement with basic survey principles (Hare, 2001), the elevation uncertainty was observed to increase towards the edges of the swath, where outer beams have a larger footprint and so a larger associated uncertainty Figure 5.17. Equally, where areas of the seafloor have been covered twice within the survey then the impact of time-variable errors can be seen. For example, in Figure 5.17 for the 2014 survey. Theoretically, by knowing both the time separation between two coincident points and observed vertical uncertainty any temporal trends in the uncertainty could be constrained and rectified. This observation also suggests that in future surveys it would be advisable to ensure that areas of the seabed are not resurveyed after a large period of time has passed as this might increase the uncertainty of the derived depth surface.
Figure 5.17: Surfaces of uncertainty derived from the FIS for the a) 2012 b) 2013/04/22 c) 2013/04/25 d) 2013/05/01 e) 2014 and f) 2015 surveys of the Algerian. Same spatial limits as Figure 5.12.
Figure 5.18: Histograms of areal and volume change between DEMs without thresholding (in grey) and with an FIS threshold only (in blue, erosion; and red, deposition).
The FIS rule system was applied on a cell-by-cell basis for all six Algerian surveys. Errors were then propagated during the creation of the DoD to generate a probability surface, where only cells with values above the 95% confidence interval are included. The results of this are presented in Figure 5.18. A comparison between the unthresholded (grey) and FIS thresholded (red and blue) areal and volume change is shown. Although in terms of area the distribution between erosion and deposition appears even, when considered in terms of volume a gap appears in the central region of the histogram (a feature not observed by Wheaton et al., 2010). Though, this result is to be expected, since, as Wheaton et al. (2010) discussed, only a change to a small surface area is required to create a peak at a higher volumetric distribution, because these are being multiplied by larger elevation changes.

Figure 5.19: Comparison of a) unthresholded, b) spatially uniformaly thresholded at ±0.2m, c) thresholded using FIS and d) thresholded using FIS and interpolation error, e) thresholded using TPU, for 2014 to 2015.

On the whole, FIS based thresholding does remove cells with lower amplitude change in a similar respect to the LoD\(_{min}\) method. However, for the periods of 2012/02/24 to 2013/04/22, 2013/04/22 to 2013/04/25 and 2014/03/26 to 2015/03/16 there were areas of the DoD (on average 2.6% of the survey area) which underwent less than ±0.2m
change (so would have been removed using the singular threshold) but were still categorised as significant change when using the FIS calculated threshold. This highlights where the LoD\textsubscript{min} is overly conservative in association with areas which have lower vertical uncertainties and where the use of the GCD methods can retrieve some information at the lower limit. Equally it can be observed that the FIS threshold also acts to remove cells across the whole range of bed-level change values. For instance, directly over the wreck structure where the slope and topographic complexity peak, the LoD\textsubscript{min} method does not exclude the likely erroneous change (Figure 5.19b), whereas the FIS method excludes much of this change (Figure 5.19c).

In order to assess the volume of data lost through the use of a threshold the information loss (one minus the ratio of volume of predicted volumetric change for that uncertainty analysis, divided by the unthresholded volumetric change) was calculated for each method. On average total information loss is increased from 45% when using the spatially uniform threshold to 52% when using the FIS surface. However, the results from the FIS thresholding appear more geomorphologically plausible.

When performing the GCD analysis using the FIS rule system an arbitrary confidence level of 95% was used. In order to test the impact of this choice on the information loss a sensitivity analysis was performed on the choice of confidence level (Figure 5.20). For the period from 2014 to 2015, as the confidence interval was increased from 50% towards 80% the net change in volume (i.e. the difference between the thresholded erosion and thresholded deposition) became less negative, after which it then became more negative, exceeding the value of the gross net change. However, crucially, the choice of confidence interval from 50% up to 99% made no difference on the overall sign of the change (net change was always negative). Equally, for all other comparisons (2012 to 2013/04/22, 2013/04/22 to 2013/04/25 etc.) the sign and order of magnitude in the net volume change is not
Table 5.5: Comparison of volume change and information lost between thresholded and unthresholded DoD. Note, the total percentage loss from original is based on the total volume not the net change.

<table>
<thead>
<tr>
<th>DoD</th>
<th>Erosion m³</th>
<th>Deposition m³</th>
<th>Net m³</th>
<th>Erosion %</th>
<th>Deposition %</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unthresholded</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012/02/24 - 2013/04/22</td>
<td>37 975.8</td>
<td>25 712.5</td>
<td>−12 263.3</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2013/04/22 - 2013/04/25</td>
<td>8171.5</td>
<td>9563.6</td>
<td>1384.8</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2013/04/25 - 2013/05/01</td>
<td>23 935.1</td>
<td>16 584.5</td>
<td>−7 350.6</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2013/05/01 - 2014/03/26</td>
<td>44 263.9</td>
<td>334 012.3</td>
<td>−10 251.7</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2014/03/26 - 2015/03/16</td>
<td>20 788.5</td>
<td>18 838.2</td>
<td>−1 950.3</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>µ</td>
<td>27 027.0</td>
<td>80 940.8</td>
<td>−6086.2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Spatially uniform 0.2m LoD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012/02/24 - 2013/04/22</td>
<td>30 311.4</td>
<td>20 583.9</td>
<td>−9 727.5</td>
<td>20</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>2013/04/22 - 2013/04/25</td>
<td>61 40.9</td>
<td>72 297.9</td>
<td>1088.8</td>
<td>25</td>
<td>24</td>
<td>49</td>
</tr>
<tr>
<td>2013/04/25 - 2013/05/01</td>
<td>12 432.6</td>
<td>90 24.9</td>
<td>−3 407.7</td>
<td>48</td>
<td>46</td>
<td>94</td>
</tr>
<tr>
<td>2013/05/01 - 2014/03/26</td>
<td>27 869.7</td>
<td>19 617.6</td>
<td>−8 252.0</td>
<td>37</td>
<td>94</td>
<td>87</td>
</tr>
<tr>
<td>2014/03/26 - 2015/03/16</td>
<td>11 285.9</td>
<td>11 056.8</td>
<td>−229.1</td>
<td>46</td>
<td>41</td>
<td>87</td>
</tr>
<tr>
<td>µ</td>
<td>1708.1</td>
<td>13 502.6</td>
<td>−4 105.5</td>
<td>35</td>
<td>45</td>
<td>80</td>
</tr>
<tr>
<td><strong>FIS (95% confidence level)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012/02/24 - 2013/04/22</td>
<td>26 405.3</td>
<td>13 036.7</td>
<td>−13 368.5</td>
<td>30</td>
<td>49</td>
<td>79</td>
</tr>
<tr>
<td>2013/04/22 - 2013/04/25</td>
<td>52 366.6</td>
<td>63 39.6</td>
<td>11 030.0</td>
<td>36</td>
<td>34</td>
<td>70</td>
</tr>
<tr>
<td>2013/04/25 - 2013/05/01</td>
<td>12 144.9</td>
<td>78 27.9</td>
<td>−4 317.0</td>
<td>49</td>
<td>53</td>
<td>102</td>
</tr>
<tr>
<td>2013/05/01 - 2014/03/26</td>
<td>24 492.9</td>
<td>19 269.2</td>
<td>−5 223.5</td>
<td>45</td>
<td>94</td>
<td>139</td>
</tr>
<tr>
<td>2014/03/26 - 2015/03/16</td>
<td>11 307.0</td>
<td>93 68.4</td>
<td>−1 938.6</td>
<td>46</td>
<td>50</td>
<td>96</td>
</tr>
<tr>
<td>µ</td>
<td>15 917.3</td>
<td>11 168.4</td>
<td>−4 748.9</td>
<td>41</td>
<td>56</td>
<td>97</td>
</tr>
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<td><strong>FIS and Interpolation Error (95% confidence level)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012/02/24 - 2013/04/22</td>
<td>15 928.1</td>
<td>51 54.6</td>
<td>−10 773.5</td>
<td>58</td>
<td>80</td>
<td>138</td>
</tr>
<tr>
<td>2013/04/22 - 2013/04/25</td>
<td>27 12.0</td>
<td>35 02.4</td>
<td>790.4</td>
<td>67</td>
<td>63</td>
<td>130</td>
</tr>
<tr>
<td>2013/04/25 - 2013/05/01</td>
<td>923.8</td>
<td>525.5</td>
<td>−398.3</td>
<td>96</td>
<td>97</td>
<td>193</td>
</tr>
<tr>
<td>2013/05/01 - 2014/03/26</td>
<td>43 746.4</td>
<td>34 54.1</td>
<td>−9 223.3</td>
<td>90</td>
<td>99</td>
<td>189</td>
</tr>
<tr>
<td>2014/03/26 - 2015/03/16</td>
<td>6 093.1</td>
<td>36 90.8</td>
<td>−2 402.3</td>
<td>71</td>
<td>80</td>
<td>151</td>
</tr>
<tr>
<td>µ</td>
<td>6 006.7</td>
<td>32 65.5</td>
<td>−2 741.2</td>
<td>76</td>
<td>84</td>
<td>160</td>
</tr>
<tr>
<td><strong>TBU</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012/02/24 - 2013/04/22</td>
<td>19 276.0</td>
<td>14 430.7</td>
<td>33 706.7</td>
<td>49</td>
<td>44</td>
<td>93</td>
</tr>
<tr>
<td>2013/04/22 - 2013/04/25</td>
<td>37 39.0</td>
<td>45 45.9</td>
<td>807.0</td>
<td>54</td>
<td>52</td>
<td>106</td>
</tr>
<tr>
<td>2013/04/25 - 2013/05/01</td>
<td>44 69.9</td>
<td>34 58.5</td>
<td>7928.5</td>
<td>81</td>
<td>79</td>
<td>160</td>
</tr>
<tr>
<td>2013/05/01 - 2014/03/26</td>
<td>13 086.1</td>
<td>90 13.6</td>
<td>−4 072.0</td>
<td>70</td>
<td>97</td>
<td>167</td>
</tr>
<tr>
<td>2014/03/26 - 2015/03/16</td>
<td>46 71.4</td>
<td>46 51.0</td>
<td>−20.4</td>
<td>78</td>
<td>75</td>
<td>153</td>
</tr>
<tr>
<td>µ</td>
<td>90 48.5</td>
<td>72 20.0</td>
<td>7670.0</td>
<td>66</td>
<td>70</td>
<td>136</td>
</tr>
</tbody>
</table>
impacted upon by the choice of threshold. Therefore, the choice of threshold would not strongly influence the overall interpretation in change between surveys.

5.2.2 Incorporation of interpolation error

As discussed in Section 2.1.4.10 of Chapter 2, interpolation of depth soundings to a raster (here, a surface is generated using the TIN to raster methodology) leads to the incorporation of further uncertainty. Using the methods described in the same section, an assessment of the impact of interpolation on the overall uncertainty of the DEM can be made. Where point density is lower and/or there is a greater bathymetric complexity the interpolated surface will likely be less representative of the true seafloor elevation. By comparing the DEM with the original surveyed values a difference surface is generated which represents the uncertainty due to the interpolation when creating the DEM. This surface is directly added to the FIS output surface in order to generate a total DEM uncertainty surface, which can then be used as a probability surface (following the same methodology as used before for the uncertainty probability surface) when comparing two DEMs.

On average, across all six surveys, interpolation from a point file to a raster with a resolution of 1m resulted in a vertical error of 0.04m. As expected, the spatial pattern of interpolation error (Figure 5.21) is very similar to that of roughness (Figure 5.15). More topographically complex areas of the seafloor (e.g. where the roughness is greater) are less well represented by the interpolated raster surface. The relationship between the interpolation error and point density is weaker (Figure 5.14). This could be as a result of the consistently high point density (therefore, seafloor features are well described) and/or as a result of the relatively coarse raster resolution (as a result interpolation does not take place over long distances).

The impact of including this interpolation surface within the GCD analysis is shown in Figure 5.19d and Table 5.5. The inclusion of interpolation error increases the total information loss by a further 28%, though as Figure 5.19d shows the inclusion of the interpolation error surface does effectively remove the remaining erroneous change observed within the outline of the wreck structure. The overall sign of the change in each DoD is not impacted by this inclusion. Therefore, as with the confidence interval, the overall quantitative interpretation of the change is not altered by the inclusion of interpolation error.

5.2.3 A-priori Total Propagated Uncertainty

As described in Chapter 2 Section 2.1.5.1, an estimate of the TPU of the MBES depth soundings can be made using a-priori estimates for the uncertainty associated with each piece of equipment (e.g. tide elevation, sound velocity, attitude sensor, etc.). Theoretically TPU should describe the vertical uncertainty of each depth value. But, as described
Figure 5.21: Interpolation error for the a) 2012 b) 2013/04/22 c) 2013/04/25 d) 2013/05/01 e) 2014 and f) 2015 surveys of the Algerian. Same spatial limits as Figure 5.12.
in Chapter 2 Section 2.1.5.1, there are limitations with this method and estimates may be inaccurate. By comparing the results of using the TPU as a probabilistic surface when creating a DoD (following the same methods as used for the FIS surface) the effectiveness of this parameter in describing the vertical uncertainty of the DEM is tested.

Concurrent with well established MBES theory, the TPU was lowest at the nadir and increased towards the outer beams of the swath (Figure 5.22). The mean TPU was lower
by 0.01m) for the 2015 survey (Figure 5.23), this is likely a result of the difference in MBES system (in 2015 the Reson 8125 system was used).

A-priori estimates of TPU were on average almost twice those observed through coincident points and had a range of just 0.015m; which seems somewhat unrealistic since the range of values from the coincident points was two orders of magnitude larger. Using a later version of CARIS (8.1.4 or later) it is possible to quantify the relative contribution of tide, lever arms etc. to the TPU (Foster et al., 2014) and thus this could theoretically be used to constrain the dominant contributor towards the TPU.

The resultant DoDs have an average information loss when compared to the unthresholded DoD of 70% (inbetween the percentage loss through the FIS surface and the combined FIS and interpolation surface) (Table 5.5). Whilst the pattern of thresholding around the wreck is relatively similar to the FIS thresholded surface (Figure 5.19e), the thresholding directly over the wreck is more comparable to the LoD_{min} DoD, i.e. large amounts of change are kept despite appearing anomalous and not the result of real change. It appears that on the whole the TPU does not as effectively capture the spatial variability of the uncertainty. This is likely a result of the over simplification of the total uncertainty budget used to generate the TPU values.
5.2.4 Comparisons between wreck and ambient areas

In order to determine the impact of the wreck structure on the seabed properties (roughness and slope) and the resultant observed uncertainty, the mean, median and interquartile range of these properties for the wreck and ambient areas are compared for the 2015 survey; Table 5.6. This survey provided good coverage of both the wreck and surrounding area, giving 979 and 4693 coincident points, respectively. Roughness over the wreck was an order of magnitude greater than for the surrounding area. Both the roughness and slope of the ambient and wreck areas had non-overlapping interquartile ranges, indicating that the two areas had distinctly different distributions of these two properties. Equally, the uncertainty over the wreck was on average four times that of the ambient bed. The observation that the slope, roughness and uncertainty were significantly greater over the wreck shows the impact of the environment on these properties is significant and further supports the use of such properties to infer the uncertainty, as has been performed in this chapter.

5.2.5 Comparison with fluvial environment

As mentioned in Section 5, the GCD method has previously been used on fluvial MBES data (Hensleigh, 2014). Here a comparison is made between the range of observed values for the two types of MBES data (Table 5.6). It was predicted that due to the diminished topographic variability of the seafloor in comparison with the riverine environment, that the marine MBES would have a smaller range of roughness and slope and that this would subsequently reduce the effectiveness of any FIS analysis. In agreement with this prediction, for the ambient (non-wreck) area the marine (Algerian) dataset had roughness values two orders of magnitude smaller than the fluvial (Wild Sheep Reach) environment. Equally, the ambient area marine data slope values were on average half those of the riverine environment. Furthermore the IQR of the slope, roughness and measured uncertainty were all significantly smaller for the ambient marine area than the fluvial environment. Whilst a smaller range of the FIS inputs (slope and roughness) is not optimum for generating a robust FIS, the output (depth uncertainty) had an equally small range and so the FIS should still perform well on the marine data. Additionally, the values of slope and uncertainty atop the wreck are far greater than for the fluvial environment, indicating that anthropogenic structures can extend the range of conditions to beyond those found in even topographically complex (fluvial) environments.

A comparison can also be made as to the impact of the environment on the point density and number of coincident points. On average the MBES surveys performed at Wild Sheep Reach had a point density of 49.5 points/m², which is greater than the average point density of any of the Algerian surveys, but smaller than the point density of seven out of the 10 surveys at the BZN 11 site. So, whilst it had a high point density the same
Table 5.6: Comparison of distribution of DEM roughness, slope and uncertainty of coincident points for a fluvial environment (Wild Sheep Reach; Hensleigh, 2014) and two marine environments (Algerian, 2015; and BZN 11, 2014). All surveys have been re-sampled to the same resolution (2ft). $Q_2$ is the median and $Q_1$ and $Q_3$ the upper and lower quartiles, respectively, giving the Inter Quartile range (IQR).

<table>
<thead>
<tr>
<th></th>
<th>Algerian: ambient bed</th>
<th>Algerian: atop wreck</th>
<th>Wild Sheep Reach</th>
<th>BZN 11</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q₁  Q₂  Mean Q₃  IQR</td>
<td>Q₁  Q₂  Mean Q₃  IQR</td>
<td>Q₁  Q₂  Mean Q₃  IQR</td>
<td>Q₁  Q₂  Mean Q₃  IQR</td>
</tr>
<tr>
<td>Roughness (m)</td>
<td>0.03 0.04 0.05 0.07 0.04</td>
<td>0.10 0.19 0.26 0.33 0.23</td>
<td>0.72 1.16 1.72 1.90 1.18</td>
<td>0.04 0.06 0.07 0.09 0.05</td>
</tr>
<tr>
<td>Slope (°)</td>
<td>2.9  5.1  6.2  8.8  5.9</td>
<td>10.0 17.2 19.6 26.4 16.4</td>
<td>4.6  8.2 12.1 15.6 11.0</td>
<td>3.2  5.0  5.7  7.2  4.0</td>
</tr>
<tr>
<td>Uncert. (m)</td>
<td>0.02 0.04 0.07 0.09 0.07</td>
<td>0.05 0.14 0.28 0.35 0.30</td>
<td>0.02 0.06 0.18 0.17 0.15</td>
<td>0.02 0.03 0.07 0.07 0.05</td>
</tr>
</tbody>
</table>
density is achievable at marine sites even with a depth of 10m. Using the relationship given in Figure 5.2 this should give on average 0.3 coincident points per square metre. However, only 19,049 coincident points were observed the 0.15km$^2$ area which was repeated twice, giving 0.06 coincident points per square metre. This order of magnitude difference could be a result of the differences in survey strategy, as the number of coincident points will be directly linked to the percentage overlap between swaths. Therefore, potentially the MBES survey lines at the Wild Sheep Reach site had less overlap than the Algerian and BZN 11 surveys.

5.2.6 Comparison with Burgzand Noord 11

In order to determine how representative the Algerian case study is of other marine sites a comparison is made with the BZN 11 time-series. In Figure 5.24 the bathymetry, roughness, slope point density and coincident point uncertainty are shown for the 2014 survey of the BZN 11. The roughness, slope and depth uncertainty do not increase over the wreck structure, highlighting how topographically smooth the Burgzand Noord wreck mounds are. Areas of elevated roughness, slope and uncertainty are observed and are associated with the crests and troughs of the surrounding bedforms.

As was observed with the Algerian data, as both slope and roughness increased over the BZN 11 site so too did the depth uncertainty of the coincident points (Figure 5.25). This finding further supports the relationship exploited at the Algerian to estimate the uncertainty using the FIS approach. Similarly to the Algerian, point density showed no obvious relationship with the measured uncertainty. Whilst, there appears to be a disparity between the non-slanted and slanted MBES coincident points, this could be due to the smaller population size of the slanted (3,233 point in comparison to 16,567 from the non-slanted surveys), thus the extreme values are not as well represented.

The distribution of the measured uncertainty values (Figure 5.26) was on the whole relatively smooth with a peak at the lowest end. For years of 2007, 2008 and 2009 the distribution is slightly less smooth and may be an indication that there were insufficient coincident points (73, 148 and 69 respectively) to fully describe the distribution of values. This supports the earlier finding that a sample of at least 150 points is required to capture the full range of possible values.

The range and mean of the slope, roughness and uncertainty at the BZN 11 are markedly comparable to the ambient bed at Algerian (Table 5.6). This suggests that the features captured by the roughness tool are comparable between the two sites. For this reason, it is unlikely that the roughness captures the grain size at these two sites, since we would anticipate a difference in the values as the Algerian site has a significantly coarser grain size than the BZN 11 (Table 4.1). This is also further supported by the disparity between the calculated grain size ($D_{50}=3.08\sigma_2 - 3.87$ (Brasington et al., 2012), giving 150mm for
the Algerian and 211mm for the BZN 11 site) and the observed grain size (1 - 2mm and 0.063 - 0.15mm, respectively). However, the relationship of Brasington et al. (2012) has only been proven down to a minimum grain size of 9mm, so this relationship may not be upheld at smaller grain sizes. Both of these findings suggest that the MBES systems are unable to resolve the sediment type at this scale. Suggesting that the roughness captured is either from larger scale seabed features (e.g. bedforms and wrecks) or is artificial roughness from the uncertainty of the soundings. Evidence for both of these causes are seen in the distribution of roughness across the Algerian and BZN 11 surveys. Whilst the former could cause increased data uncertainty, the latter is a direct observation of this uncertainty, so is more likely to have a stronger relationship with the coincident point uncertainty.

The similarity in range and mean of the coincident point uncertainties between the two marine surveys is a somewhat surprising result, considering that two very different navigation systems were used for the surveys: in the case of the Algerian, DGPS was used
Figure 5.25: Relationship between slope, roughness, point density and elevation error from coincident points for all Burgzand Noord 11 surveys. Non-slanted MBES shown in red and slanted in blue. Details for slanted and non-slanted surveys given in Table 4.11.

and for the BZN RTK used, which has been reported to reduce vertical uncertainty by an order of magnitude (Ernstsen et al., 2006a). This observation could be a result of the inability of the coincident point method to capture the true accuracy of the depth soundings, as, highlighted in Chapter 2 Section 2.1.5.1 Method 8, this method only captures the precision of the MBES data. Therefore, the incorporation of a surface describing the accuracy of the data, e.g. an a-priori TPU surface, may be required to give a better estimate of the uncertainty of the MBES data.

5.2.7 Effectiveness of GCD methods on the Algerian time-series

Total information loss across all analyses ranged from 20% (Spatially uniform ±0.2m LoD_min) all the way up to 98% (FIS and interpolation uncertainty threshold), with a mean of 62% (35% higher than Wheaton et al., 2010 and 15% higher than Hensleigh, 2014). Unlike the fluvial settings observed by Wheaton et al. (2010), the site of the Algerian has not undergone any processes which would lead to large areas of contiguous
change. Therefore, although the information loss is significantly higher than in other studies, this could be a result of the environment rather than the methods used.

Coincident point uncertainty alone (without any further GCD analysis) proved to be a powerful tool in isolating the relative differences in uncertainties across and between surveys. For example, the impact of using a different tide gauge for the 2012 survey was immediately obvious when the histograms of coincident point elevation differences were compared. More generally these values can also be compared to other surveys (e.g. the surveys of the BZN 11 site) to determine overall data quality.

Whilst the a-priori values of TPU had the same order of magnitude as the coincident point uncertainty their small range and spatially variability did not fully capture the real spatial variability in uncertainty (e.g. the elevated level of uncertainty directly over the wreck structure). Whereas, the FIS generated surface and the interpolation uncertainty surface performed well at describing the spatial variability in uncertainty.

Whilst using the FIS and interpolation uncertainty surfaces dramatically increased the
information loss (there was an average increase in information loss of 35% between using the ±0.2m threshold and the FIS and interpolation threshold), the resultant DoDs appeared more geomorphologically plausible (e.g. over the wreck structure there was no detectable change). Therefore, the GCD method is deemed more appropriate than the use of a fixed spatially uniform threshold. In Section 6.3.2 an outline is presented as to how this method could be developed further.
Chapter 6

Discussion and Conclusions

6.1 Overview

This thesis aimed to progress our understanding of the taphonomy of historical shipwreck sites through the use of repeat Multibeam Echo-Sounder (MBES) bathymetry surveys. This was achieved, firstly, by developing a systematic and robust methodology for handling bathymetry time-series, environmental data and archaeological data. Following which, five MBES bathymetric time-series of wreck sites, extending up to seventeen years in length, some with sub-annual time-steps, were brought together. These time-series covered a broad range of environmental conditions:

i. *Richard Montgomery*: tidally dominated (weakly asymmetrical), extensive sediment supply (sands), stable morphological context

ii. *Scylla*: storm dominated, sediment limited (sand), stable morphological context

iii. Burgzand Noord site: tidally dominated (strongly asymmetrical), extensive sediment supply (sand), basin-wide seafloor deepening

iv. *Stirling Castle*: tidally dominated (asymmetrical), extensive sediment supply (gravels), kilometre-scale bank migration

v. *Algerian*: tidally dominated (symmetrical), extensive sediment supply (gravels), stable morphological context

By quantitatively describing the temporal variability of these wreck sites the impact of the differing marine environments on the wreck site’s taphonomic pathway was hypothesised. Finally, a method for quantifying the spatially variable uncertainty (Geomorphic Change Detection; GCD) was adapted for use with MBES data, allowing for a more robust attempt at evaluating the ‘real’ change between repeat MBES surveys.
6.2 Key findings

Only over the past decade have high resolution MBES systems become relatively affordable and accessible to maritime archaeologists. As a result, fewer than ten projects have employed time-series of MBES to quantify historical shipwreck site variability and reported their findings (Table 1.1). Of these, the longest published was just four years in total and made up of just five repeat surveys (Bates et al., 2011). This paper and others (e.g. Ernstsen et al., 2006a; Manders, 2009) exemplify how MBES time-series were at the time still relatively novel and thus, much of the focus of these earlier studies was on demonstrating the capability of MBES time-series in capturing change at wreck sites. As a result, little exploration was carried out as to the causes and controls of these processes.

Once these studies driven by methodological motives had been published, archaeologists were, finally, in a position to utilise these time-series to explore shipwreck site taphonomy. Understandably, case studies were selected to ensure that site formation processes were captured, and so often focused on those wreck sites known to have undergone some disturbance. For example: a tropical cyclone (Orange and García-garcía, 2009; Stieglitz and Waterson, 2013; Trembanis et al., 2013), trawling (Brennan et al., 2016) or illegal digging (Manders, 2009). These studies offered the opportunity to examine the impacts of disturbances on wreck sites, but shed little light on the ambient and longer term taphonomic processes.

Whilst a reasonably sized collection of wreck site MBES time-series now exists, perhaps the only study so far that has drawn a comparison between sites is Quinn and Boland (2010). Here, two sites, each with two repeat bathymetric surveys (one a singlebeam time-series) were compared and contrasted. Quinn and Boland (2010) were able to conceptualise models for the development of these two distinctly different sites and as a result allowed future researchers to develop more realistic, accurate and higher-definition site formation models.

From this literature review a need for a more extensive comparison of wreck site MBES time-series was identified. To this end, through this thesis, the most comprehensive attempt to date has been made at bringing together wreck site MBES time-series from a range of environments, covering time-steps from two days up to multi-annual and with observational periods of up to seventeen years. In Chapter 1 three major research questions were proposed. The findings for each of these are now presented.
6.2.1 How temporally variable are shipwreck site systems?

In Chapters 3, 4 and 5 temporal variability was shown at each wreck site through the presentation of DEM of Difference (DoD). Whilst each DoD was unique and showed differences in the spatial distribution and magnitude of change, for the purposes of comparison between sites the temporal variability can be considered as a whole through the average absolute change (Figure 6.1). For each time-step the absolute change was taken. This was then converted to absolute change per year by dividing change by the time period represented by the time-step. Finally, a mean was taken of all of these surfaces.

When presenting the data as DoD the combined vertical uncertainty of the data (e.g. ±0.3m for Richard Montgomery) were shown using a distinct separate colour. We have more confidence in the temporal variability values (absolute bed-level change per year) at those sites with a higher repeat survey frequency (a smaller interval between surveys) and longer time-series (assuming that each of the surveys is independent). Therefore, to quantify the error of the average absolute change the fractional error is reduced by the factor $1/\sqrt{n}$, where $n$ is the number of intervals (e.g. since the Richard Montgomery time-series is made up to 13 intervals this gives an average absolute bed-level change error of 0.08m).

The resultant figures display the coherency, magnitude and spatial coverage of the bed-level change. There are three distinct scales over which this change is observed to occur both spatially and temporally:

**Minimal variability:** At the Algerian, Scylla, BZN 4, 8 and 11 the average absolute mean change was just 0.13, 0.07, 0.09, 0.19 and 0.17m/year, respectively (the same boundaries for the BZN sites were used as in Section 4.3.3.2). This change did not occur in distinct areas and was on the whole, non-coherent. Furthermore, for the Scylla time-series and to a lesser extent the Algerian time-series, much of this change was aligned in bands perpendicular to the survey-lines. Any change likely related to errors in the initial data, particularly in the attitude sensor data. Over some areas of the Algerian survey the change appears more sinuous and could relate to bedform migration. However, it was noted that there were some large horizontal offsets between the surveys when comparing the position of the wreck and other fixed features. These could not be corrected for since the residuals of the correction were consistently greater than the required shift (Root Mean Squared (RMS)>1m). As a result, any horizontal changes between surveys of less than 1m could not be resolved using these data and so the observed change could relate to positional errors.

At all four of these wreck sites the magnitude of the change does not significantly increase closer to the wrecks, indicating that where scour/depositional features present (restricted to within a few metres of the wreck structures), that they are stable over the time-series.
Figure 6.1: Average absolute bed-level change for the a) *Scylla*, b) *Algerian*, c) Burgzand Noord, d) *Richard Montgomery*, and e) *Stirling Castle*, wreck sites, overlain on the most recent survey’s hillshade. Study area extent shown for each BZN wreck.
Median variability: At the *Richard Montgomery*, BZN 3 and 10 bed-level change was on average 0.34, 0.33 and 0.28m/year, respectively. This change occurs in more coherent patches generally a few 10’s of metres in size. This change was largely constrained to the already present scour pit and so indicates reorganisation of material within the wreck-influenced area. At the *Richard Montgomery* this reorganisation resulted in bed-level change occurring over a large range (±3m). In spite of this, the net change remained within the survey uncertainty (±0.3m) and the location of the maximum scour depth remained within a 9m$^2$ area, demonstrating the overall stability of the wreck site. Outside of the wreck areas the magnitude of the change dropped to below 0.1m/year, indicating that the presence of the wrecks have enhanced the rate of change of bed-level within their area of influence.

Maximal variability: At only one site, the *Stirling Castle*, was this type of temporal variability observed. Here, kilometre scale, coherent, large magnitude (on average 0.47m/year) change was observed right across the site (a 350m by 1,000m area). There is no discernible impact of the presence of the wreck on the average rate of change, suggesting that the site scale ambient conditions dominate over any wreck-scale processes.

In summary, three key temporal/spatial scales of change were observed at the five case study sites. Only over medium temporal (approximately 0.3m/year) and spatial (few 10’s of metres) scales does the presence of the wreck structure have a significant impact on the temporal variability of the seafloor.

6.2.2 How do site conditions affect this variability?

The drivers of the three scales of change identified in the previous section are now considered in terms of: i) the flow conditions, ii) the wreck geometry and iii) the gross-morphology.

6.2.2.1 Hydrodynamic conditions

By considering the strength of the tidal/wave flow at the seabed in relation to the grain size the flow conditions at the site can be determined (Table 6.1). Both at the *Richard Montgomery* and *Scylla* ambient flow conditions are insufficient for bedload transport, i.e. ‘clear-water’ conditions. In agreement with this observation, bedforms are not found at these two sites. Even with the enhanced shear stresses associated with flow past a flow-perpendicular bluff obstacle (3 - 4 times the ambient shear; Smyth and Quinn, 2014; Whitehouse, 1998) the tidal flow at the *Scylla* is insufficient for scouring to occur. As a result no real change through tidally-induced flow is observed at this site.

By contrast, at the *Richard Montgomery*, tidal currents are close to the required threshold for transport. As a result, obstacle-enhanced flow is sufficient for scouring. Whilst
Table 6.1: Summary of bed shear stress properties at each wreck site and implications for sediment transport. Observation of bedforms is for the area immediate to the wreck.

<table>
<thead>
<tr>
<th></th>
<th>Tidal ($\tau_c$) or wave ($\tau_w$) dominant?</th>
<th>Ambient conditions above or below threshold for transport?</th>
<th>Bedforms observed?</th>
<th>Predicted conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Richard Montgomery</strong></td>
<td>$\tau_c$</td>
<td>Below</td>
<td>No</td>
<td>Tidally dominant, clear-water</td>
</tr>
<tr>
<td><strong>Scylla</strong></td>
<td>$\tau_w$</td>
<td>Below</td>
<td>No</td>
<td>Wave dominant, clear-water</td>
</tr>
<tr>
<td><strong>Burgzand Noord</strong></td>
<td>$\tau_c$</td>
<td>Above (Potentially insufficient data)</td>
<td>Yes</td>
<td>Tidally dominant, live-bed</td>
</tr>
<tr>
<td><strong>Stirling Castle</strong></td>
<td>$\tau_c$</td>
<td>Approx. equal to</td>
<td>Yes</td>
<td>Tidally dominant, live-bed</td>
</tr>
<tr>
<td><strong>Algerian</strong></td>
<td>$\tau_c$</td>
<td>Approx. equal to</td>
<td>Yes</td>
<td>Tidally dominant, live-bed</td>
</tr>
</tbody>
</table>

the Richard Montgomery has been shown not to be affected by storm events and to have reached some quasi-equilibrium state, still medium-scale bed-level change is observed at this site. Models have shown that even once a scour pit has been observed to reach equilibrium state that unsteady flow due to fluctuating components (horseshoe- and lee-wake vortex flows) can be on the order of 3 - 4 times larger than the mean bed shear stress (Sumer et al., 1997). Thus, erosion and re-deposition of material within a scour pit is possible even when the site conditions remain stable.

The hydrodynamic conditions alone cannot be used to explain all of the observed change or lack of. For example, at the Algerian, BZN 4, 8 and 11 ambient conditions are sufficient for transport, confirmed by the presence of bedforms. Yet, medium-scale change was not observed at either of these two sites. Thus, the geometry of the wrecks must also be an important controller of change.

### 6.2.2.2 Obstacle geometry

As can be seen in Figure 6.2 the wrecks presented here offer a wide range of geometries and hence, obstacles to the flow. These variables can be succinctly described by the width to height ratio (W:H), where the width is the length of the face relative to the prevailing flow direction. The flow width rather than the obstacle beam is used, since it is the size of the face presented to the prevailing flow, which is of importance when considering scour processes.
Figure 6.2: Point clouds of wreck structure (grey) and surrounding seabed (brown), with ambient occlusion performed using qPCV plugin, for a) *Stirling Castle* (Sep. 2005), b) BZN 11 (2006), c) *Scylla* (2013), d) *Algerian* (2015) and e) *Richard Montgomery* (2012). Trihedron indicates up (blue), north (green) and east (red). No vertical exaggeration has been applied.
Whilst the length, height and beam of the *Richard Montgomery* and *Scylla* are comparable, more than 180,000m$^3$ of material has been scoured from around the *Richard Montgomery*, yet virtually no scouring or deposition is observed at the *Scylla*. This is because the *Scylla* is near perfectly aligned to the prevailing wave environment (the wreck was aligned this direction purposefully to reduce the damage done to this artificial wreck site by storms) and as a result has a much lower W:H (of just 1.5) than the *Richard Montgomery* (which as a W:H of 13). Interestingly, despite being caused by oscillatory-induced transport, the scour observed around the leading end of the *Scylla* is comparable to a cuboid orientated into the flow. Suggesting that the type of flow, in this case, was not of importance.

Similarly to the *Scylla* the *Algerian* offers a relatively low W:H (11) (Lambkin *et al.* (2006) observed that changes in object aspect ratio had the largest impact on key length scales when the obstacle had a W:H of 10 or less) and poses a minimal obstruction to flow, resulting in just two small scour pits (extending less than 3.5m away from the wreck) and a ‘tail’ of deposited sediment emanating from both the bow and stern (a more detailed description as to how this feature formed is given in Chapter 4, Section 4.5.3.1). Since the flow is largely unaltered there is very little temporal variability at these sites.

In good agreement with physical models (Saunders, 2004), a strong positive correlation was observed between the wreck height and both the maximum scour pit depth (r=0.86, p<0.01) and length (r=0.81, p<0.01) for the *Stirling Castle* and BZN sites. This relationship was also upheld when the height of the wreck either increased or decreased. The observation implies that those sites with a more stable wreck mound geometry will have a more stable scour pit. Very little change is observed downstream of BZN 4, 8 and 11, whilst the change downstream of BZN 3 and 10 is on the order of two times larger. This is because, in accordance with scour theory, any changes in object aspect ratio will alter the maximum scour depth and extent. At BZN 3 and 10 the physical protection was extended during the observation period, raising the maximum wreck heights by 1.0 and 0.7m, respectively and increasing the W:H ratio for both wrecks by 4. Equally the location of the maximum scour depth was more stable at those sites which didn’t change much in height (maximum scour depth positions were confined to a radius of 3m at the BZN 8, in comparison to a 41m radius at BZN 3). Altering the profiles of these three wrecks will have destabilised the equilibrium and resulted in greater rates of change between surveys.

### 6.2.2.3 Gross-morphology

In response to rising seabed levels around the wreck, the *Stirling Castle* was also observed to undergo relative change in W:H relative to the flow, from 17 in 2002 to 29 in 2009. The decrease in the obstruction to the flow that the wreck presented resulted
in a decrease in the spatial extent of the associated scour pit (the location of the maximum scour depth shifted 34m closer to the wreck structure). However, as noted in Section 6.2.1, the change at this site occurred over kilometres and at a rate of greater than 0.5m/year. The only explanation for this scale of change is that the Goodwin Sands bank as a whole is migrating. This was explored through the use of multi-decadal historical charts (Section 4.4.1.3). By doing so it was observed that the bank margin to the east of the wreck is migrating west at a rate of approximately 8m/year, explaining the large-scale trend in bed-level change observed across the MBES time-series. Past records indicate that the *Stirling Castle* was buried under the sandbank up until the 1970’s (Whitewright, in review). The MBES and historical chart data indicate that if the observed trend continues the site could be buried under 5m of sediment within the next two decades.

Whilst the *Richard Montgomery* is also situated on a large sand-bank, this site did not undergo bed-level change at the same rate as the *Stirling Castle*. Again, using historical charts the multi-decadal evolution of the bank feature was observed. The centroid (the centre position of the bank) migrated by just 57m from 1924 to 2008. This distance is potentially within error, i.e. there has been no change of the bank’s position over the 84 year period. Therefore, the lack of major temporal variability at the *Richard Montgomery* is connected to the stability of its gross-morphological setting. These findings illustrates the importance of considering the gross-scale site geomorphology when attempting to constrain the past, present and future taphonomy of a wreck site.

In summary, an understanding of hydrodynamic principles (bed shear stresses), combined with basic scour principles (W:H and orientation of the wreck), can be used to explain observed taphonomy. However, it is still necessary to have an appreciation of the gross-geomorphology through a consideration of larger spatial (100’s m to km) and temporal (multi-annual to multi-decadal) scales.

### 6.2.3 In terms of a process-response system, how open or closed are wreck site systems?

As mentioned in Chapter 1, Section 1.3, the taphonomic processes at wreck sites must be better constrained in order to progress our understanding of the formation and trajectory of these sites and develop better methodologies for managing these archaeological deposits. Here, the taphonomy is explored by considering each site (the wreck and its surrounds) as a process-response system. The implications of these findings are then discussed in terms of the heritage management of the site.

Figure 6.3 shows a schematic of the system state with time of each of the five case study wreck sites, adapted from Quinn and Boland (2010). Broadly each wreck site follows
Figure 6.3: Schematic of the system state of the a) SS Richard Montgomery, b) Algerian, c) Scylla, d) Burgzand Noord wreck and e) Stirling Castle, in the context of equilibrium state throughout the MBES survey period. The system state of the Algerian is shown as a dashed line since although no variability was observed it is feasible that change below the level of detection could have occurred. Equally, only one survey has been made since the Stirling Castle begun a phase of reburial and so the latter section of the schematic is speculative. Adapted from Quinn and Boland (2010).
a different taphonomic pathway over the observation period. Both the *Richard Montgomery* (Figure 6.3a) and the *Algerian* (Figure 6.3b) are effectively closed systems throughout the observational period. However, the processes at both of these sites are ultimately quite different. The former is observed to undergo internal change (scrambling processes; Muckelroy, 1998) resulting in a steady-state equilibrium, whilst the latter effectively undergoes no observable change, static equilibrium. Whilst both of these processes result in the maintenance of the system state, as no material is lost or gained, the spatial patterns of sites undergoing internal reorganisation will be altered with time; thus, making it more of a challenge to reverse engineer the site.

Unlike the *Richard Montgomery* and the *Algerian*, the initial scouring phase of the *Scylla* (Figure 6.3c) was captured by the bathymetry time-series presented in Chapter 4. As predicted (Figure 1.4) the site underwent a rapid phase of change and material loss, after the initial period *in situ*, before reaching a stable-state equilibrium. By comparing the scour extent to that of a neighbouring wreck (the SS *Eagan Layne*) with a good amount of confidence, the future pathway of the *Scylla* can be forecasted as maintaining this system state for an extended (multi-decadal) period. Therefore, it can be inferred that this site will not likely become buried or undergo significant further scouring. This is advantageous, as the site is used both as an artificial reef and an attraction for recreational divers. The management of this site should therefore focus on the impacts of chemical wear, which is already preventing the site from being penetrated by divers due to the collapse of fittings, bulk heads and deck heads, thought to be due to the effects of dissimilar metals used in the original construction (National Marine Aquarium, 2014).

Following the trigger event of the completion of the Balgzand dike in 1924 and the Afsluitdijk dike in 1932, the Burgzand Noord site has been undergoing uninterrupted year-on-year bed-level loss and so is described as being at dynamic equilibrium with its surrounds (Figure 6.3d). Following the theory of process-response systems the rate of change at the site has been decreasing, this is suggestive that in the future the site will reach a new and stable system state, much like the *Scylla* after its initial perturbation. However, this is further complicated by the more recent perturbations at the Burgzand Noord sites through the implementation of protective measures. Those wrecks which had further protective matting applied to them during the observation period underwent larger changes in bed-level and scour morphology. In an area with such a high density of shipwrecks consideration must be paid to the potential impacts that destabilising a wreck site’s morphology may have on the downstream region.

Whilst the *Stirling Castle* was also exposed to a triggering event (Figure 6.3e), which will likely lead to the complete burial of the site over the next few years, the future of the site is less certain since the evolution of the sand bank on which the wreck is situated is likely to lead to the re-exposure of the site. The repeated disturbance of this site prevents a steady-state of equilibrium from becoming permanently established. This poses a complicated set of circumstances in terms of the management of this site, as whilst the site is
protected from physical, chemical and biological wear when buried, once re-exposed the
site has been observed to undergo degradation. As a result, physical protection would
only be beneficial during the periods of exposure, making the application of such meth-
ods less worthwhile.

In summary, wrecks which have undergone some kind of perturbation, whether
natural or anthropogenic (e.g. a storm event, the migration of a sandbank over
the site or the implementation of physical protection methods) during their
observation period acted as open systems, either gaining or losing material
to the surrounds. Whereas, those wrecks where the environmental conditions
remained near-constant did not lose or gain material with their surroundings,
so acted as closed sites.

6.3 Future developments

6.3.1 Expand the range of case studies

Presently in maritime archaeology an assessment of a wreck site’s taphonomy is often
made based upon a singular site survey. It has been shown in this thesis that some wreck
sites are at dynamic or steady state equilibrium with their surrounds. Therefore, singu-
lar surveys at these sites may not capture the prevailing conditions at the site. In order
to constrain the temporal variability of these sites repeat surveys are required. Already
some parallels have been drawn between these sites and the range of temporal variability
that they display (Section 6.2.1). An understanding of the temporal variability of wreck
sites is of enormous value to archaeologists, since it allows them to tailor site survey pro-
grams to optimise time and resources by only surveying the site when change is forecast
(e.g. at a closed site such as the Algerian intra-annual surveys would not be optimal since
there is little change to the system over short time-scales).

In this thesis, connections have been made between the environmental conditions of the
wreck sites’ and their taphonomic pathways. Theoretically, by understanding other wreck
sites’ Meteorological and oceanographic (Metocean) and geological conditions, inferences
could be made as to their taphonomy. However, this assumes that the relationships ob-
served here between the environmental conditions and the observed temporal variabil-
ity will be upheld at all other sites. Therefore, one large consideration when comparing
these five wreck sites is how representative they are of the other 3 million wreck sites
worldwide (UNESCO, 2014). Fundamentally there is something unique about these five
sites; they are all presently on the surface of the seabed (hence why they can be surveyed
using MBES). This has implications for the possible taphonomic pathways of the sites
that have been studied here, as the wreck has both: i) not been destroyed or lost in its
entirety and ii) not remained buried. So already we have excluded the two possible end-member scenarios from this study.

In terms of their environmental conditions the five wreck sites presented here do cover a wide range: tidally dominated (weakly asymmetrical), tidally dominated (strongly asymmetrical), storm dominated and sediment limited, dominated by large-scale geomorphological processes and sheltered. Noticeably, not a single one of these case studies is situated on an exposed bedrock surface. Which does potentially support the conclusion’s of Throckmorton (1977, pg.47), that wrecks situated on exposed rock are not often preserved. Though, perhaps equally likely, this is a result of the incredibly small sample size of wrecks in this study. Clearly and unsurprisingly, there are gaps in the spectrum of environments captured by these five case studies. In order to have a better understanding of the taphonomic pathways of a wreck site further time-series should be considered from a broader range of environments, e.g. rocky, muddy bottom, equally strong wave and tidal components etc. In doing so a more robust empirical understanding of the relationship between the environment and taphonomy will be gained, making this knowledge applicable to a larger number of wreck sites.

6.3.2 Broaden the applicability of Geomorphic Change Detection

In Chapter 5 Geomorphic Change Detection (GCD) methods were applied to the Algerian time-series. To estimate the vertical uncertainty of the MBES surfaces a 2-rule Fuzzy Inference System (FIS) was used, which incorporated the values of slope and roughness. The demonstrable relationship between these properties allowed a more robust estimation of the spatially variable uncertainty of the Digital Elevation Model (DEM)s. However, the FIS developed here is only, so far, applicable to the Algerian time-series alone. This is because it has only been trained using coincident points from these surveys. A number of generic FIS models have been developed (Bailey, 2015), which have applicability to multiple surveys (Airborne Laser Scanner, Global Positioning System (GPS), Terrestrial Laser Scanner and Total Station) and so feasibly such a FIS could be developed for marine MBES data.

In order to ensure the FIS was robust, a training set from the full potential range of conditions (slope, roughness, etc.) and from a number of different sonar systems, would have to be used. Once established this FIS could then be applied to datasets where estimates of the spatially variable vertical uncertainty cannot be made (e.g. when only pre-gridded data are available such as in the case of the Richard Montgomery, Stirling Castle, Burgzand Noord and Scylla). This would then allow for a more robust estimation of the real change between DEMs, even when MBES metadata is lacking.
6.3.3 Cloud-to-cloud comparison

Where surfaces have large vertical gradients, e.g. glacial moraines, cliff faces and even scour pits (scour pit slope angles in excess of of 60° have been observed around monopiles; Melling, 2014), the comparison of two DEMs cannot operate properly. Information density is decreased proportionally to surface steepness (i.e. a vertical surface cannot be described by a DEM) (Lague et al., 2013). In order to prevent this loss of information the original point clouds can be directly compared. Furthermore, directly using the point clouds circumvents the requirement for interpolation, which was shown in Chapter 4 to have a significant impact on the total uncertainty of the DEM. Methods for comparing two point clouds directly are still in their infancy (but are growing in popularity) and are computationally more demanding than comparing two DEMs. However, the methodological advantages are noteworthy.

Perhaps the most commonly used method to compare two point clouds is the Multiscale Model to Model Cloud Comparison (M3C2) algorithm available as a plug-in within the CloudCompare software (Dietrich, 2014; Lague et al., 2013; Stumpf et al., 2015; Westoby et al., 2015). This method calculates the cloud-to-cloud distances based on the local orientation of the point relative to the surface normal. An advantage of this method is that it provides an output of spatial variable confidence interval (based upon the local surface roughness) which can then be used to threshold the change in a similar method to the GCD methods in Chapter 5. Certainly at sites where large areas of the seafloor are steep (e.g. the scour pit of the Richard Montgomery, where average slope are around 10°) cloud-to-cloud comparison is likely to result in a decreased loss of information in comparison to the DoD analysis. In order to ensure the true variability at the wreck site is captured cloud-to-cloud comparison should be adopted.

6.4 Best practice

In Chapter 2 after each source of MBES uncertainty was introduced recommendations as to the best practice to reduce and/or constrain this uncertainty were given; these were then summarised in Table 2.2. Through Chapters 3 to 5 as these methods were put into practice further methods for identifying and constraining uncertainty were developed. These are shown in Figure 6.4. In summary, all of the pathways ensure that the best estimate of the uncertainty is made depending on how complete the dataset is (i.e. if the GCD method can be carried out and the a priori Total Propagated Uncertainty (TPU) can be estimated, then ensure they are). Finally, the estimated surfaces of uncertainty (either spatially fixed or spatially variable, depending on the methodology) are then used to threshold the DoD and ensures that only statistically significant change is shown and analysed.
Figure 6.4: Workflow for estimating the uncertainty of MBES surveys and applying this to the DoD. The dashed-outline box indicates where further development is required before this methodology can be carried out (described in Section 6.3.2).

Furthermore, even without completion of the full GCD methodology surfaces such as roughness, slope and point density; and the calculation of coincident point error can be incredibly useful tools to begin to understand and constrain sources of error within the MBES survey.
6.5 Concluding remark

This thesis presented repeat (intra-annual; annual; and decadal) MBES surveys for five shipwreck sites (the largest published collection of shipwreck site MBES time-series to date), including the longest published near-annual MBES time-series of any marine structure. Through quantifying the temporal variability at each site it has been shown that with a good understanding of a shipwreck site’s Metocean and geological conditions and an understanding of basic scour and depositional processes (such as those observed through physical modelling), a level of appreciation for and predictability of the site’s taphonomy is achieved. It is this awareness of the prevailing forces at the site that must be met in order to ensure that heritage management choices are informed and work in tandem with the environment.
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